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Systems evaluation for computer graphics rendering of the total appearance of paintings

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Systems Evaluation for Computer Graphics Rendering of the Total Appearance of Paintings

by

Lin Chen

A Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of Master of Science
in Color Science

Chester F. Carlson Center for Imaging Science
College of Science

Rochester Institute of Technology
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M.S. DEGREE THESIS

The M.S. Degree Thesis of Lin Chen
has been examined and approved by the
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thesis required for the
M.S. degree in Color Science

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Systems Evaluation for Computer Graphics Rendering of the Total Appearance of Paintings

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Lin Chen

Submitted to the
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in partial fulfillment of the requirements
for the Master of Science Degree
at the Rochester Institute of Technology

Abstract

One of the challenges when imaging paintings is recording total appearance, that is, the object's color, surface microstructure (gloss), and surface macrostructure (topography). In this thesis, various systems were used to achieve this task, and a psychophysical paired comparison experiment was conducted to evaluate their performance. A pair of strobe lights arranged at 60° from the normal on either side of the painting captured color information where the strobes produced either directional or diffuse illumination geometry. By adding a third strobe, arranging them 120° apart annularly, and cross polarizing, diffuse color and surface normal maps were measured. A fourth strobe was added and the four lights were rearranged 90° apart annularly, capturing similar data. This system was augmented by two scanning linear light sources arranged perpendicularly, facilitating the measurement of spatially varying BRDF and specular maps. A laser scanner was used to capture surface macrostructure and was combined with the diffuse color maps from the four-light configuration. Finally, a dome illumination system was used with software

developed by Conservation Heritage Imaging to produce color maps. In all, eight different configurations were achieved and used to image three small paintings with a range of appearance attributes. Twenty-five naive observers compared computer-graphic renderings to the actual painting and judged similarity in terms of total appearance, gloss/shininess, texture, and color. Although the rankings varied with painting, two general trends emerged. First, the four-light configuration with or without the independent laser scanning produced images visually equivalent to conventional strobe illumination. Second, diffuse illumination was always ranked lowest.

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Chapter 1

Introduction

1.1 Problem Statement

Digital archiving of cultural heritage is aimed to preserve, present, and impart to future generations our irreplaceable cultural wealth in the form of digital images. Digital archiving allows users to browse images freely on display through the Internet such that observers are not required to observe the real painting. Traditionally, paintings are photographed in a single image based on a photographer's subjective decisions. The single image records only a single viewpoint under a specified light source and only a limited range of material properties. This method reduces the observer's interactive experience by removing any interplay among the lighting, work of art, and observer. Thanks to the advancement of digital imaging, computing, transmission, and storage technologies, digital archiving systems of paintings enable conveyance of the total appearance of painting including not only accurate color information but also surface properties. Furthermore, observers can have the interactive experience of interplaying with an image based on varying illumination and viewing angles.

To achieve a realistic rendering of the art object, information about the geometries of objects, light sources and the observer or the detector in the scene, and strength of light sources and field of view of the detector or the observer, etc. are generally required (Berns, 2006). The total appearance of a painting is decided by a number of factors such as spatially varying spectral reflectance factor, surface macrostructure (depth or surface normal), and surface microstructure (bi-directional reflectance distribution function, BRDF) (Berns et al., 2012b). The spatially varying spectral reflectance factor and BRDF can be measured by a spectral camera under a specified light source (or multiple light sources) under various geometric conditions. Depth information can be obtained with a laser and structured light scanners (Taylor et al., 2002), close range photogrammetry (Duarte & von Altrock, 2005), or inferred from the object's shading. Alternative representations of depth include measuring surface normal in the three-dimensional space, which is a vector direction perpendicular to the tangent plane to that surface, and polynomial texture maps (Malzbender et al., 2001), which is an imaged-based technique that reconstructs the surface maps based on varying lighting directions.

1.2 Research Objectives

A number of systems have been developed to reconstruct the total appearance of paintings utilizing different algorithms. The purpose of this thesis was to evaluate the performance of these different systems for recovering the most important properties of artwork. Several paintings were imaged and measured, and their physical characteristics were modeled using different systems. These systems can reconstruct different important physical properties of a painting's appearance, each with its own algorithms. Then, computer graphics techniques were used to produce the appearance under specified lighting or observing conditions. The goals were to determine which technique performed the best and to determine if this technique could replace a conventional imaging system. A psychophysical paired comparison experiment was conducted to evaluate a total of eight different systems, and four paintings were selected for evaluation. Twenty-five observers took part in the experiment and four sets of questions were asked based on different properties of the painting's appearance. The four sets of questions were generated based on a questionnaire answered by professional experts. Finally, the experimental results were analyzed and the performance of the different techniques were ranked.

1.3 Thesis Overview

The thesis is organized as follows:

Chapter 2 is an overview of previous research dealing with digital archiving of art paintings. Details such as spectral color reproduction and surface geometry construction are defined. Psychophysical methods and relative requirements are described within this section.

Chapter 3 details the systems evaluated in this research. This chapter covers a description of the system and its algorithms as well as experimental setup. The advantages and disadvantages of different systems are also compared and summarized.

Chapter 4 introduces two main experiments in this research: a survey on digitization issues of physical properties of paintings and a psychophysical evaluation from a paired comparison experiment. In the first part, the survey design and questionnaire details are listed. Experimental setup, frame work, data collection, and data processing are also described.

Chapter 5 interprets and analyzes the data collected from the series of experiments outlined in Chapter 4. This chapter includes a discussion about each question and cross-correlation between the series of psychophysical experiments.

Chapter 6 presents the conclusions from the analysis and discussion described in Chapter 5 and outlines future research to obtain representation of artwork paintings.

Chapter 2

Background

Archival digital art paintings are widely used for various applications including web-based images, color reproduction, scientific study, art history, and other scholarly studies (Berns, 2001). An accurate recording of a painting's physical properties is very important for digital imaging. Achieving this accurate recording is difficult and requires specialized hardware, optimal imaging practices, and specialized software. Digital archiving of art paintings representing the total appearance of art painting, is not limited to recording one single static image under one specified illumination and viewing angle. The total appearance can be decided based on both spectral information for color reproduction and surface information describing surface appearance. In reality, a painting's appearance varies greatly in surface topography and gloss. The minimum physical properties for computer graphics to create a virtual experience are color, surface macrostructure (depth or surface normal), and surface microstructure (gloss), as a function of its planar position. The function defines the artwork's total appearance (Berns et al., 2012a).

2.1 Total Appearance of Art Painting

2.1.1 Color

The color diffuse albedo can be defined spectrally or colorimetrically. Colorimetric images require color management, and this method is described by the International Color Consortium. While spectral imaging methods have been developed recently and summarized by Fischer (Fischer & Kakoulli, 2006), Pelagotti (Pelagotti et al., 2008), and Pillay Pillay et al. (2008), a painting's color appearance, as we know, varies along with the changing illumination and viewing angle, and it is also sometimes affected by the shadows of the objects. The spatially varying spectral reflectance factor can be measured by a spectral camera under a specified light source (or multiple light sources) and various geometric conditions. Hawkins (Hawkins et al., 2001) proposed an approach to render cultural artifacts based on capturing the reflectance fields of objects, but a large number of images are required. Tominaga (Tominaga et al., 2004) presented a method for imaging and rendering only oil paintings using a multi-band camera. Berns (Berns, 2001) gave a comprehensive review of multispectral imaging for achieving color-accurate archiving of art paintings. This previous research shows that spectral imaging technology has been widely used in conservation and archiving of art works.

2.1.1.1 Reconstruction Methods

A calibration target is first utilized to create the transform matrix M between a camera's signals R, G, and B and spectral reflectance factors R_λ. This allows the camera signals of other targets to be transformed into spectral reflectance factor or XYZ values.

The Pseudo-Inverse Method This method uses linear minimization (pseudo-inverse) to obtain the transformation from n channels to reflectance values, as shown as Eq. 2.1. The number of channels varies between five and eleven . The camera data are either the average or individual pixel values for each training sample.

$$\begin{pmatrix} R_{\lambda=380} \\ . \\ . \\ . \\ R_{\lambda=730} \end{pmatrix} = M \begin{pmatrix} C_1 \\ . \\ . \\ . \\ C_n \end{pmatrix} \tag{2.1}$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = M \begin{pmatrix} C_1 \\ . \\ . \\ . \\ C_n \end{pmatrix} \tag{2.2}$$

Non-Linear Optimization Following the method of 2.1.1.1 , the generated matrix M is set as the starting value to minimize the average ΔE_{00} error for D50 and the 1931 standard observer. This method performs non-linear optimization, which accounts for the change of reflectance curve. This method is limited to average pixel value for each training sample.

2.1.1.2 Matrix R Theory

The Matrix R theory can be used to reconstruct spectra based on reflectance similarity as well as colorimetric similarity. The Matrix R theory (Zhao & Berns, 2007) combines a metameric black spectrum and a colorimetrically matched spectrum to produce a new spectrum. This new spectrum is both similar to the measured spectrum in reflectance space as well as colorimetrically.

Metameric Black The use of metameric black is to minimize the error between reconstructed spectra and measured spectra. A linear transformation can be easily adopted to produce the projection matrix $\mathbf{R}$ as

$$\mathbf{R} = \mathbf{A} \times \mathbf{A}^{\dagger} \tag{2.3}$$

where $\mathbf{A}^{\dagger}$ is the pseudo inverse of $\mathbf{A}$, and $\mathbf{A}$ is the ensemble of the product of color matching functions and an illuminant. The projection matrix can be split into two parts. By applying $\mathbf{A}^{\dagger}$ on any spectrum, one would obtain the projection scalar of the spectrum on each matching function in the ensemble. Multiplying $\mathbf{A}$ by the scalar leads to a summation that gives a projection of the spectrum on the ensemble. The output of the projection gives a spectrum that can be decomposed as a linear combination of all spectra in the ensemble. Based on the projection matrix $\mathbf{R}$, we can also have a nulling matrix shown as

$$\mathbf{I} - \mathbf{R} \tag{2.4}$$

where $\mathbf{I}$ is the identity matrix. The nulling matrix basically gives a spectrum that cannot be projected on the ensemble subspace. Using the nulling matrix, a metameric black can be obtained as

$$\mathbf{B} = (\mathbf{I} - \mathbf{R}) \times \mathbf{N} \tag{2.5}$$

where N is the original spectrum.

Colorimetric matching Using a camera profile, one can transform the scalar camera signals to linear signals by Eq. 2.6,

$$\mathbf{D_{L,\ i}} = (\alpha_i \mathbf{D_i} + \beta_i)^{\gamma_i} \tag{2.6}$$

The linear camera signals are denoted by $\mathbf{D_{L,\ i}}$ for each i^{th} channel; α_i, β_i and γ_i are the gain, offset, and gamma values for ith channel; and $\mathbf{T}$ is a matrix with its column representing tristimulus values for each patch. Using these signals and linear error minimization, one can obtain a transformation matrix between the tristimulus value and the linear camera signals as described below

$$\mathbf{T} = \mathbf{M_c} \times \mathbf{D_L} \tag{2.7}$$

where $\mathbf{T}$ is an array of the tristimulus values and $\mathbf{D_L}$ is an array of the linear camera signals. The transformation matrix $\mathbf{M_c}$ can be further optimized by minimizing color difference.

Eventually, the reconstructed spectrum can be built as

$$\hat{\mathbf{N}}_{\mathbf{c}} = \mathbf{A}(\mathbf{A}'\mathbf{A})^{-\mathbf{1}}\hat{\mathbf{M}}_{\mathbf{c}}\mathbf{D}_{\mathbf{L}} + (\mathbf{I} - \mathbf{R})\hat{\mathbf{N}} \tag{2.8}$$

In this method, pixel data are used to estimate spectral reflectance factor by Eq. 2.1 while average data are used to estimate colorimetric data by Eq. 2.2 and Eq. 2.6.

2.1.2 Surface

2.1.2.1 BRDF

To achieve photorealistic renderings of paintings, it is necessary to characterize the surface reflectance properties. The Bidirectional Reflectance Distribution Function (BRDF) (Nicodemus, 1977), is a function that describes the relationship between the directional reflected radiance and the directionally incident irradiance. This function can be used to model material reflectance properties. The BRDF is denoted symbolically as f_r, as shown in Eq. 2.9 (Nicodemus, 1977):

$$f_r(\theta_i, \phi_i; \theta_r, \phi_r) = dL_r(\theta_i, \phi_i; \theta_r, \phi_r; E_i)/dE_i(\theta_i, \phi_i)[sr^{-1}] \tag{2.9}$$

where θ and ϕ together indicate a direction, the subscript i indicates quantities associated with incident radiant flux, the subscript r indicates quantities associated with reflected radiant flux, E_i is incident irradiance, L_r is reflected radiance, and d indicates a differential quantity. The BRDF function can be expressed in terms of viewing and illumination geometries, which is illustrated in Fig. 2.1.

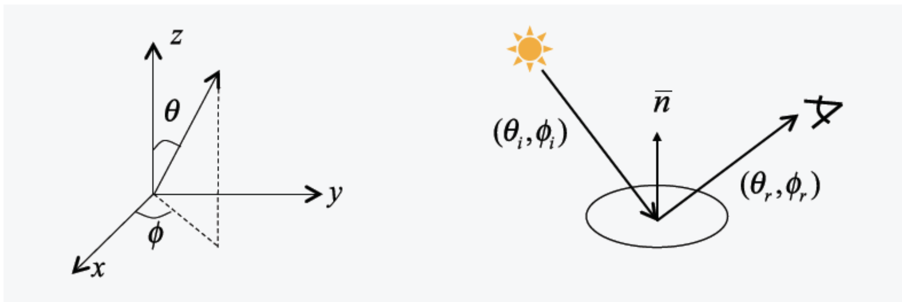


Figure 2.1: *BRDF expressed in terms of viewing and illumination geometries.*

The BRDF measurements can be conducted using a gonio-reflectometer for one specific lighting and viewing direction at a time. The standard algorithm is to measure the BRDF point cloud from images and to optimize it by one of the BRDF models. The BRDF models can be derived based on phenomenological-based or physical models using a limited set of measurements. The Phong (Phong, 1975), Blinn (Blinn, 1977), and Ward (Ward, 1992) models are phenomenological models. Physical models include Torrance-Sparrow (Torrance & Sparrow, 1967), Cook-Torrance (Cook & Torrance, 1982) and Oren-Nayar (Oren & Nayar, 1994) models. The Phong and Ward models were the two most popular models based directly on measured data. The Blinn model applied the Torrance-Sparrow physical model to computer graphics. All of these models try to reconstruct the specular and diffuse components of reflectance. Chen (Chen et al., 2007) tested the Phong and Torrance-Sparrow models for acrylic paint based upon comparing computer-graphics rendered and photographed images on an LCD display. The results suggest that the BRDF model may not be a critical factor when rendering artwork except for highly glossy materials and geometrical accentuated specular highlights.

2.1.2.2 BTF

The Bidirectional Texture Function (BTF) was defined by Dana (Dana et al., 1999), which allows the BRDF to vary spatially across a surface parameterized by u, v.

$$BTF_{r,g,b}(\Theta_i, \Phi_i, \Theta_e, \Phi_e, u, v) \tag{2.10}$$

The BTF does not calculate the ratio of excitant (Θ_e, Φ_e) to incident (Θ_i, Φ_i) energy like the BRDF. Instead, the BTF records the pre-integrated lighting condition for a particular light source. This method provides samples of the BTF from photographs, and problems exist due to the high dimensionality of the model. A large number of images are required to adequately sample this space, and the camera must be accurately calibrated to keep two dimensions u, v constant.

2.1.2.3 Surface Normal

Surface normal is a vector direction that is perpendicular to the tangent plane of a surface. The surface normal is determined from two or more images based on varying the direction of the incident illumination while holding the viewing direction constant. The normal vector at a point (x_0, y_0) on a surface $z = f(x, y)$ can be represented by

$$\tilde{\mathbf{N}} = \begin{bmatrix} \frac{\partial f(x,y)}{\partial x} \\ \frac{\partial f(x,y)}{\partial y} \\ -1 \end{bmatrix} \tag{2.11}$$

In most cases, the unit normal vector form is preferred as

$$\mathbf{N} = \begin{bmatrix} \frac{\partial f(x,y)}{\partial x} \\ \frac{\partial f(x,y)}{\partial y} \\ -1 \end{bmatrix} / \sqrt{\frac{\partial f(x,y)}{\partial x}^2 + \frac{\partial f(x,y)}{\partial x}^2 + 1} \tag{2.12}$$

The normal vector on a surface can be used to simulate light interaction with the object. Surface normal can also be integrated to form the height map.

A straightforward way to calculate surface normal is through photometric stereo. Two important techniques are used to reconstruct surface properties. One method, the photometric stereo (Woodham, 1980a) technique, is the most straightforward way to measure surface normal, which uses lights positioned in fixed locations. Another one is polynomial texture maps (Malzbender et al., 2001), which is an imaged-based technique that reconstructs the surface maps based on varying lighting conditions.

2.1.2.4 Polynomial Texture Mapping

Polynomial Texture Mapping (PTM) was developed by Malzbender (Malzbender et al., 2001) as a new form of texture mapping to reconstruct surface color under varying lighting conditions. The two devices he used are shown in Fig. 2.2. In this method, the camera (detector) is mounted and fixed in the apex of the dome and samples are placed on the floor. Multiple registered images are acquired with varying light source directions and are directly interpolated to approximately reproduce the appearance.

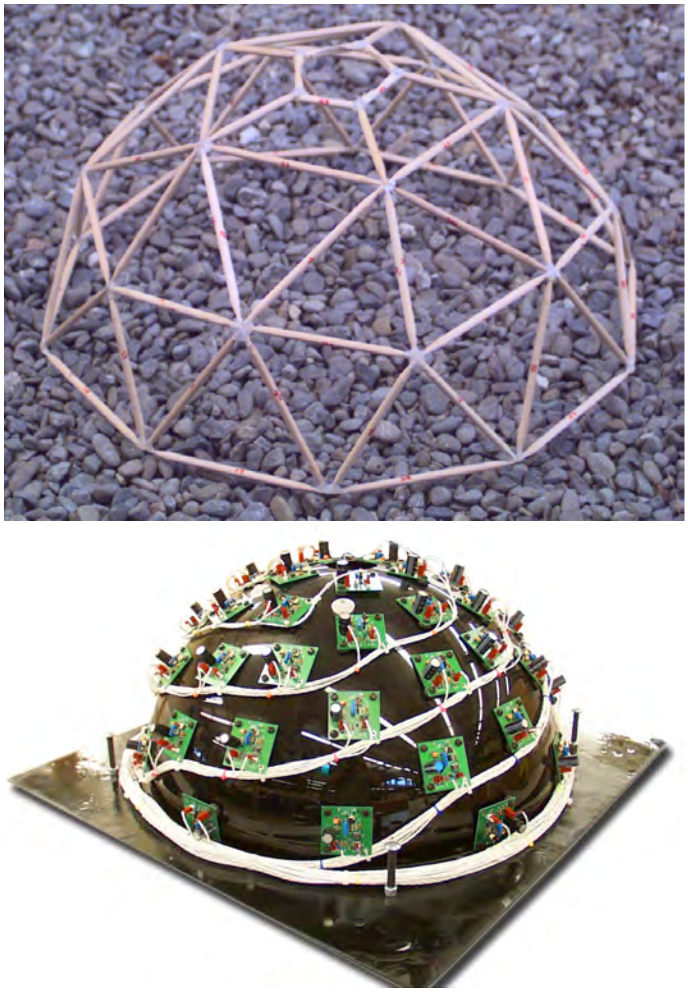


Figure 2.2: *Two devices for collecting PTMs. (Malzbender et al., 2001)*

PTM assumes the intensity is dependent on lighting vectors up to the second order. Such bi-quadratic dependency is expressed as

$$I(x,y;l_x,l_y) = a_0(x,y)l_x^2 + a_1(x,y)l_y^2 + a_2(x,y)l_xl_y + a_3(x,y)l_x + a_4(x,y)l_y + a_5(x,y), \tag{2.13}$$

where (l_x, l_y) are projections of the light vector into the point (x, y) and I is the resultant surface luminance at that point. The coefficients $(a_0 - a_5)$ can be fitted by illuminating the surface with multiple lightings similar to a photometric stereo setup. The system equation can be written as

$$\begin{bmatrix} l_{x1}^2 & l_{y1}^2 & l_{x1}l_{y1} & l_{x1} & l_{y1} & 1 \\ l_{x2}^2 & l_{y2}^2 & l_{x2}l_{y2} & l_{x2} & l_{y2} & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ l_{xn}^2 & l_{yn}^2 & l_{xn}l_{yn} & l_{xn} & l_{yn} & 1 \end{bmatrix} \times \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix}. \tag{2.14}$$

PTM parameters can then be obtained using linear regression. This approach requires that the object inside a fixed size dome, thus limiting the object size. Furthermore, Eq. 2.13 does not well account for the specular parameter, the specular component is not directly modeled and must be handled separately Malzbender et al. (2001). PTM is basically an image-based rendering method and lacks an explicit surface reflectance model. It is used as a qualitative tool to study the surface properties of artwork Malzbender et al. (2001).

2.1.2.5 Photometric Stereo

The photometric stereo (Woodham, 1980a) technique is the most straightforward way to measure surface normals by using lights positioned in fixed locations. For a Lambertian surface, the reflected light with lighting $\mathbf{L} = [l_x, l_y, l_z]$ for a point with surface normal N can be calculated as

$$I = \rho \mathbf{L} \cdot \mathbf{N} \tag{2.15}$$

where ρ is the diffuse surface albedo. Given the surface normal map $\mathbf{N}$ and albedo ρ, one can predict the captured intensity I from Eq.2.15 if the lighting direction $\mathbf{L}$ is known. On the other hand, the surface normal can be calculated by captured images with varying illuminations.

For illumination $\mathbf{L}^i = [l_x^i, l_y^i, l_z^i]$, the captured intensity can be expressed as

$$I^i = l_x^i \rho N_x + l_y^i \rho N_y + l_z^i \rho N_z \tag{2.16}$$

where for multiple illuminations

$$\begin{bmatrix} I^1 \\ I^2 \\ \vdots \\ I^n \end{bmatrix} = \begin{bmatrix} l_x^1 & l_y^1 & l_z^1 \\ l_x^2 & l_y^2 & l_z^2 \\ \vdots & \vdots & \vdots \\ l_x^n & l_y^n & l_z^n \end{bmatrix} \times \begin{bmatrix} \rho N_x \\ \rho N_y \\ \rho N_z \end{bmatrix}. \tag{2.17}$$

With linear regression, the surface normal can be obtained as

$$\begin{bmatrix} \rho N_x \\ \rho N_y \\ \rho N_z \end{bmatrix} = \begin{bmatrix} l_x^1 & l_y^1 & l_z^1 \\ l_x^2 & l_y^2 & l_z^2 \\ \vdots & \vdots & \vdots \\ l_x^n & l_y^n & l_z^n \end{bmatrix}^{\dagger} \times \begin{bmatrix} I^1 \\ I^2 \\ \vdots \\ I^n \end{bmatrix} \tag{2.18}$$

where † indicates pseudo-inversion. In addition, the unit vector constraint is stipulated as

$$\sqrt{N_x^2 + N_y^2 + N_z^2} = 1, \tag{2.19}$$

such that one can obtain the surface albedo and surface normal.

Tominaga and Tanaka (Tominaga & Tanaka, 2008) captured images using a six-channel imaging system and reconstructed the geometry using photometric stereo. They also rendered the whole painting with common parameters of specular reflectance.

Furthermore, many other techniques have been developed to reconstruct surface properties of the object. Haneishi (Haneishi et al., 2001) developed a gonio-spectral imaging system at Chiba University to reproduce the optical properties of 3D objects. Guidi, et al. (Guidi et al., 2003) applied 3D scanning to the field of art restoration. They scanned Leonardo Da Vinci's painting *Adorazione dei Magi* to diagnose the state of the painting's wood support.

2.1.2.6 Microstructure (Gloss)

Surface microstructure (gloss) can be reflected by spatially varying reflectance. Specular reflection is directly dependent on the surface of the object and closely related to its surface normals. Specular reflection is spectrally non-metals and its color is, therefore, determined by the color of the light source. Gardner, et al. (Gardner et al., 2003) introduced a technique for estimating the spatially varying reflectance properties of a surface using linear light source reflectometry. In their system, two passes of the linear light source at different nearly perpendicular angles were used as input data. First, they created a reflectance table of how diffuse and specular reflectance lobes would appear under moving the linear light source illumination. Next, a series of intensity values to the tabulated reflectance lobes of each pixel were compared for deciding the reflectance model parameters. Utilizing this system, per-pixel surface normals and reflectance parameters were estimated. This technique was used for scanning nearly flat objects, and the apparatus is shown in Fig. 2.3.

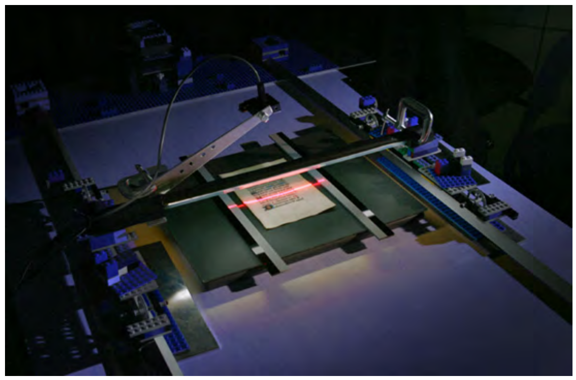


Figure 2.3: *The linear light source apparatus. (Gardner et al., 2003)*

Most of these techniques not only reproduce one property of the painting but also obtain more properties at the same time. These techniques enable the construction of a complete system that not only achieves high color accuracy, surface topography and gloss, but also enables the observers to interact with the art painting under varying illumination and viewing angles.

2.1.3 Flat Fielding

Due to the complexity of the camera, the digital count directly captured from the camera cannot be used in its original captured form for this analysis.

Flat fielding is a necessary step. The goal of the flat fielding is to remove artifacts in the image due to spatial variation of the sensor and the optical path. The dark noise of the camera especially needs to be removed simply by subtracting a black image. Generally, a white board is used for flat fielding to compensate for the non-uniformity of both the sensor and illumination as Eq. 2.20 .

$$R_\lambda = \frac{L_\lambda}{L_{white,\ \lambda}} \times factor_\lambda \tag{2.20}$$

where R_λ is relative reflectance, L_λ and $L_{white,\ \lambda}$ are the radiance of image and the white, respectively, and $factor_\lambda$ is the flat fielding function.

2.2 Psychophysics

Psychophysical methods are tools to quantify the relationships between physical stimulation and perceptual appearances (Pelli & Farell, 1995). Many psychophysical techniques are used for creating ranking of perception and sensation. The most popular methods (Gescheider, 1997) are summarized in Table 2.1.

Table 2.1: *Psychophysical methods (Gescheider, 1997).*

thresholds	scaling	
method of adjustment	indirect	direct
method of limits	rating	equisection
method of constant stimuli	paired comparison	magnitude production
	ranking	magnitude estimation
	category scaling	

The method of paired comparison is a popular method to evaluate the effect of various algorithms on image quality or for quantifying the change in a perceptual characteristic such as perceived contrast and sharpness. Thurstone (Thurstone, 1927) presented a simple theory of the discrimination process that allows the construction of an interval scale based on comparisons of pairs of stimuli. This method has been widely used for research in the application and analysis of paired comparison data.

During the experiments, when the observer selects the prevailing member of the pair, one is added in the column of a frequency matrix. The standard paired-comparison method also assumes that the comparison of A-B is the same as B-A, and that in an A-A or a B-B comparison, one sample will be selected over itself 50% of the time. Therefore, a result of the last two assumptions is that only $n(n-1)/2$ comparisons need be made, and that the proportion matrix is symmetric, that is, $p_{i,\ j} + p_{j,\ i} = 1$. For this method, all combinations are displayed to the observer with "left-right" order, which will average out position effects. The position of a pair A-B, which means A is presented on the left and B on the right, is assumed to be different from the comparison of pair B-A. This assumption leads to an increase in the number of comparisons from $n(n-1)/2$ to $n(n-1)$.

Probability is often considered Gaussian and the cumulative probability is often represented by the area under the curve. The position along the normal x–axis is often called z-score (or the z–value). A z-score is the number of standard deviations that a given x value is above or below the mean. If z represents the z-score for a given x value, then z-score is calculated by Eq. 2.21:

$$z = \frac{x - \mu}{\sigma} \tag{2.21}$$

where μ is the mean value and σ is standard deviation. Then, a standard normal curve shown in Fig. 2.4 can be used to determine the probabilities.

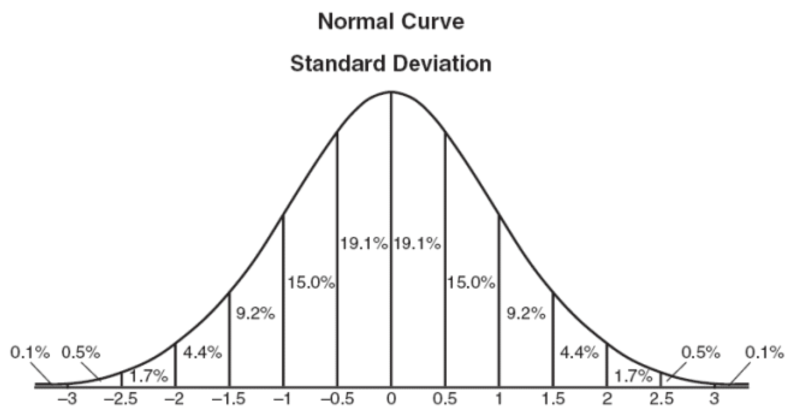


Figure 2.4: *Normal curve standard deviation.*

The average of the z-score is used to obtain the relative ranking of the image quality of the reproductions based on different techniques. Due to the limitation of the number of the observers, Montag (Montag, 2006) researched a function that can capture the observed standard deviation from the stimuli and observations. The observed standard deviation is estimated based on Eq. 2.22. The 95% confidence interval on scale values are calculated from Eq. 2.23:

$$\sigma_{obs} = b_1(n-b_2)^{b_3}(N-b_4)^{b_5} \tag{2.22}$$

$$CI = \pm 1.96\sigma_{obs} \tag{2.23}$$

where $b_1 = 1.76,\ b_2 = -3.08,\ b_3 = -0.613,\ b_4 = 2.55$, and $b_5 = -0.491$.

A confidence interval (CI) is used to indicate the reliability of an estimate, and in principle, differs from sample to sample. A 95% confidence interval reflects a significance level of 0.05, and the confidence interval contains the parameter values that, when tested, should not be rejected with the same sample. An interval cannot specify a certain value but instead a range within which the parameter is estimated to lie.

Chapter 3

Experimental Systems

Artwork can be imaged for documentation and reproduction purposes. Artwork such as paintings and drawings often have spatially varying spectral reflectance factor and surface structures. Imaging such artwork has a very long history and multiple systems can be used to achieve this task (Berns et al., 2005a). In this chapter, eight systems were implemented and their performances evaluated using psychophysical experiments. Each method is described briefly, including the underlying mechanisms as well as the advantages and disadvantages of their use.

3.1 Three-Light System

The three-light system is a polarization-enhanced three-light photometric stereo system (Woodham, 1980b) for capturing the appearance of art paintings (Berns & Chen, 2012). Photometric stereo (Woodham, 1980a) is a computer vision technique for estimating the surface normals of objects by observing the object under different lighting conditions.

Two assumptions are made for the traditional photometric stereo method. One assumption is that the object is Lambertian and the other is that distant point light sources are used. In terms of the two assumptions, the surface normal can be obtained by inverting the linear Eq. 3.1:

$$I = n \times L \tag{3.1}$$

where I is a vector of m observed intensities, n is the surface normal, and L is a $3 \times m$ matrix of normalized light directions. Since n consists three unknowns, there are at least three equations to obtain the unknowns. In this system, three lights are used where the light's direction vectors are not in the same plane.

Art paintings are usually non-Lambertian, often with substantial specular reflectance. To estimate the result accurately, polarized filters are used to remove specular reflection (Born et al., 1999) in the three-light system. The cross polarization scheme for eliminating specular reflection is illustrated in Fig. 3.1, and the system setup is shown in Fig. 3.2.

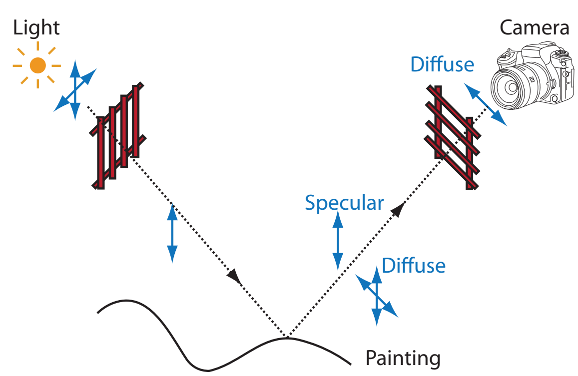


Figure 3.1: *Schema of the cross polarization for eliminating specular reflection.*

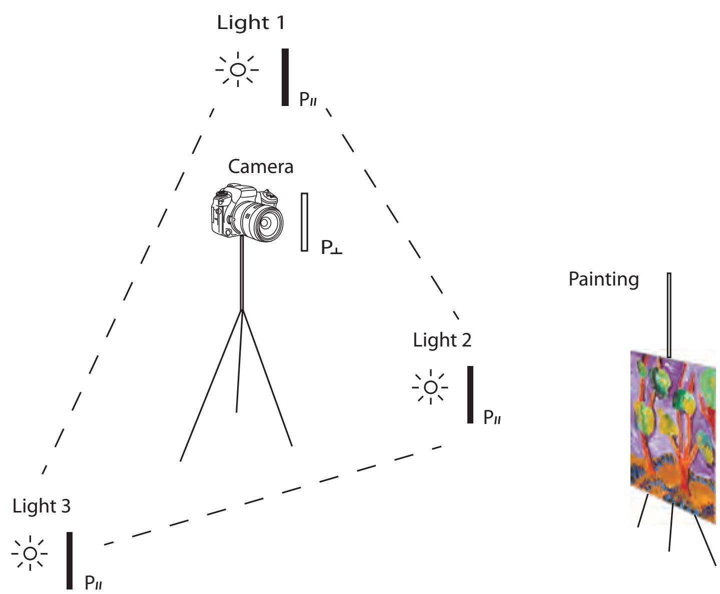


Figure 3.2: *System setup of three-light system.*

In this system, there are three polarized light sources and one camera coupled with a corresponding polarizer (Nee, 1996). The polarizers in front of the three-lights have the same polarization orientation while the polarizer in front of the camera is orthogonal to the other three. Three images will be captured as each light is turned on sequentially. The surface normal can be obtained based on Eq. 3.1, and diffuse color can be calculated in terms of the two-filter method (Berns et al., 2005b). Specular albedo and roughness can be defined by the users, assuming the entire painting has uniform gloss.

3.2 Four-Light System

Similar to the three-light system, the four-light system adds another strobe light as well as an affixed polarizer (Berns et al., 2012b). The configuration of the lights is arranged so that each light is placed symmetrically 90° apart within an annulus and 45° from the object plane. Again, the system can take both cross and parallel polarization images. The cross polarization image is used to compute diffuse color as well as surface normal while the parallel polarization is used to create conventional images. The surface normal $\mathbf{n}$ is calculated using

$$\mathbf{n} = \mathbf{L}^{\dagger}\mathbf{I} \tag{3.2}$$

where $\mathbf{n}$ is the surface normal, $\mathbf{L}$ is a 4-by-3 matrix defining normalized light directions for the four lights, and $\mathbf{I}$ is the reflected light intensities from the object. Notice Eq. 3.2 resembles Eq. 3.1, except a pseudo-inverse operation ($\dagger$) is used to estimate the surface normal rather than direct inversion.

The experimental setup is illustrated in Fig. 3.3 and the real setup is shown in Fig. 3.4.

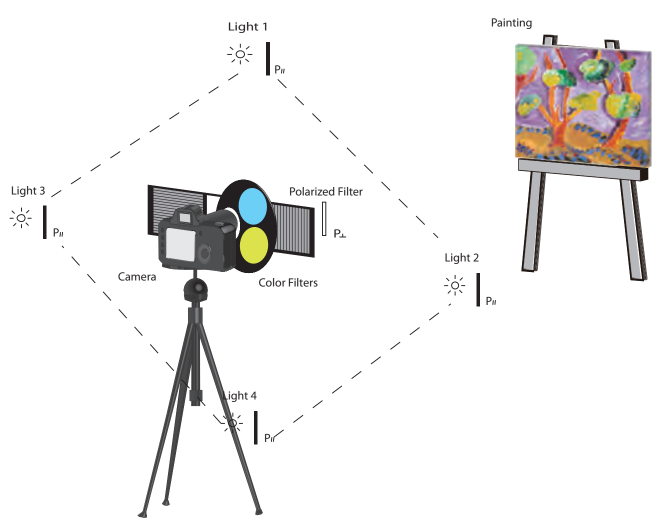


Figure 3.3: *The four-light experiment setup.*

Figure 3.4: *The four-light experimental setup.*

The lighting position is shown in Fig. 3.5 and Fig. 3.6. The polarization image is able to present higher detailed images and suppresses glare thus reveals more contrast images than conventional imaging systems. Also, a big advantage is fewer shadows. The configuration of the lights improves the polarization contrast of the image thus producing more accurate surface normal. It also reduces noise in the images, and the results are generally better than the three-light system. Furthermore, the four-light system resembles a traditional capturing system and is easier to realize in museums.

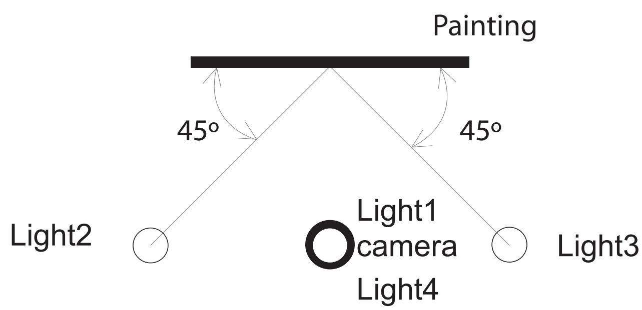


Figure 3.5: *Top view of four-light setup.*

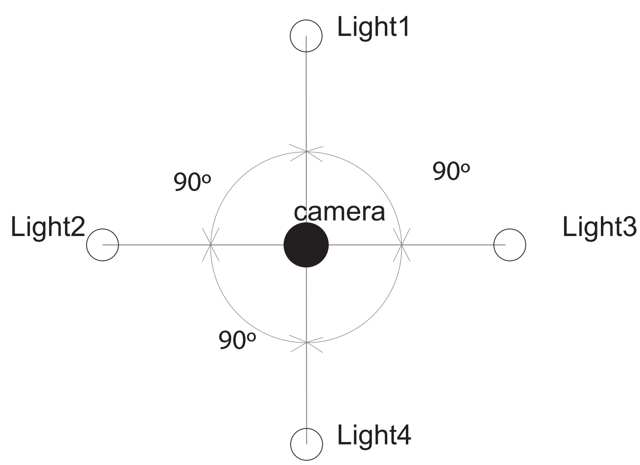


Figure 3.6: *Front view of four-light setting.*

3.3 Linear Light System

The linear light system is a novel method used to capture the spatially varying appearance of paintings using polarization-enhanced 2D linear source reflectometry with integrated multispectral imaging. This method performs well for imaging paintings with large variation in glossiness and significant subsurface scattering since the light source only illuminates a limited area on the target at one time. It recovers color-accurate diffuse albedo, surface normals, specular albedo, and specular roughness for each pixel. The diffuse and specular reflections are modeled separately. This is done because specular reflection is in high contrast, and it is spectrally non-selective making its color mainly determined by the color of the light source. Also, specular reflection is directly from the surface of the object and related to surface normal. In contrast, diffuse reflection predominantly determines the color of the object. In this system, a polarization-based method is used to separate diffuse and specular reflection. The 2D linear source reflectometry is exploited to densely sample the specular reflection and high resolution surface normals, specular albedo, and specular roughness for each pixel (Dorsey et al., 2008). The diffuse albedo is measured accurately by the multispectral imaging system. The final created model can be used to render different images under various illuminants, including point source, and linear light source (Wong et al., 1997).

Digitizing the spatial features of paintings is difficult because of the various diffuse and specular reflections. A big challenge exists regarding modeling highly specular reflections, since it requires very dense spatial and angular sampling. Due to the the large variation in glossiness, high dynamic range appearance (Debevec & Malik, 2008) is introduced, and this makes direct capture of these paintings problematic using low dynamic range imaging techniques. Also, some paintings are multi-layered and rich with subsurface scattering that can pollute the surface reflection and create erroneous 3D data when scanning opaque objects. Furthermore, some rich, fine geometrical details at the mesostructure scale require the system to have high enough resolution to reveal the fine details, even higher than the naked eye (Marschner et al., 1999). Most importantly, the size of paintings is varied and an ideal system should be scalable and adaptable for different sized paintings.

The main illumination, a linear neon tube, has several advantages. It is simpler than 2D or 3D illuminations and more efficient than a point source. It is inexpensive, extendable, flexible, and easy to construct and move. The linear light sources can be vey thin, such as Cold Cathode Fluorescent (CCF) tubes used for display backlighting. However, the contrast ratio between the specular and diffuse reflection is lower compared to a point source (Chen & Berns, 2012).

A system was designed at MCSL (Chen & Berns, 2012) based upon the basic philosophy of linear source reflectometry by using a linear source (Schilling, 1997) and (Gardner et al., 2003).The experimental setup is illustrated in Fig. 3.7, and the real setup is shown in Fig. 3.8.

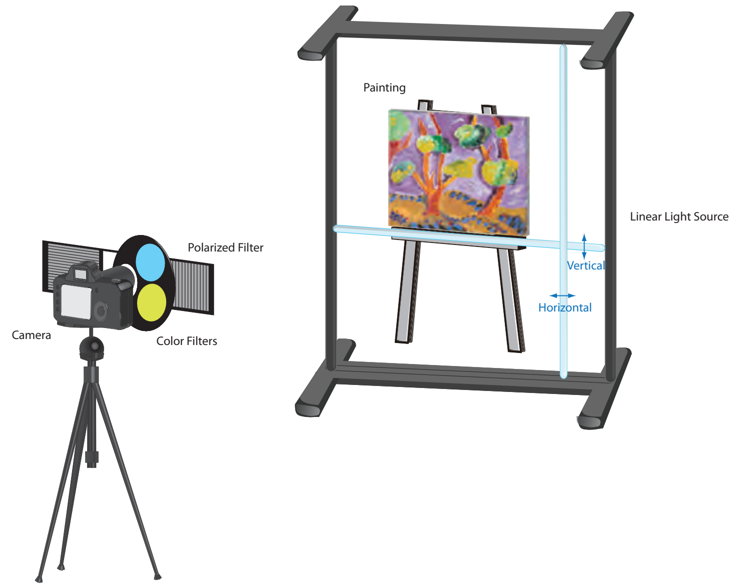


Figure 3.7: *Illustration of the linear light system experimental setup.*

Figure 3.8: *The linear light system experimental setup.*

In this system, polarization was used to separate the diffuse and specular components. By cross-polarizing the light source and camera, only diffuse reflectance is captured while parallel polarization captures both specular and diffuse components. Specular albedo can be obtained from the difference of these results. Two lights were arranged perpendicularly and independently controlled as compared to the 55-degree inclination used by Gardener (Gardner et al., 2003). This geometry avoids possible perspective foreshortening that would sacrifice resolution and introduce more self-occlusion.

3.4 Reflectance Transformation Imaging (RTI)

RTI is a computational photographic method used to capture a subject's surface shape and color and enable the interactive re-lighting of the subject from any direction.

RTIViewer was used to estimates surface normal using the multiple images. This normal map was used in its viewer along withe the color maps that are rendered with PTM for specific geometry. The multi-mathematical enhancement modes can be used to enhance surface shape and color attributes as well as optimize sharpness and brightness. The enhancement functions of RTI do not reveal real surface information of the physical object and use a series of different processing filters.

The RTI system is based on multiple digital photographs of a subject shot from a stationary camera position. The RTI images use Polynomial Texture Maps or PTMs technique to reconstruct images, which means they can be analyzed using similar 3D lighting techniques. Unlike a typical photograph, reflectance information is derived from the three-dimensional (3D) shape of the imaged subject and encoded in the image per pixel (Malzbender et al., 2001). The synthesized RTI image simulates the light reflection at any position based on a two-dimensional (2D) photographic map. The RTI system does not perform color management, flat fielding, or compensate for non-point source behavior. The value of RTI is in the interactive viewing of objects with different processing filters. The most useful filter is called "specular enhancement." It simply uses a metallic BRDF and the user can blend between the actual image and a metallic rendering of the surface normal with Phong model (Phong, 1975) with adjustable parameters.

3.5 Conventional Image Capturing Systems

The most common way of capturing a painting's appearance is to take an image using commercial cameras with one or two lights located away from the painting's surface normal, typically between 45° and 60°. One can adjust the lighting conditions and the camera positions to capture images that accentuate or decentuate surface topography. However, this approach cannot recover surface normals. This traditional method can be used as ground truth to validate the quality of the image rendering systems. The lighting can be predominantly directional using conical reflection or diffuse using "soft-boxes," a box-like attachment with a diffuser facing towards the object.

3.6 Laser Scanning System

Laser scanning is a very accurate approach to measure the height map of paintings (Malzbender et al., 2001)(MacDonald & Robson, 2010). The basic design of a laser scanner is very straightforward. The surface height is measured from the displacements in the image of a projected laser line. Laser scanning results can often be considered as ground truth to validate the rendered surface normals. However, one disadvantage of laser scanning is its inability of producing accurate color information despite using red, green, and blue lasers. For this thesis, only the height map information was used. The diffuse albedo from the four-light system.

3.7 Diffuse System

The color image from the diffuse system is generated by averaging the four diffuse albedo images from the four-light system.

3.8 Systems Comparison

A comparison of the advantage and disadvantage of each system is shown in Table. 3.1.

Table 3.1: *Comparison between the different appearance rendering models.*

System	Advantages	Disadvantages
RTI	varying highlights, shadows, darker illumination	inaccurate color
Conventional System	can be considered as truth	no surface normal
Soft-box System	produced soft viewing effect	blurred edges, no surface normal
Three Light System	color-accurate diffuse albedo,surface normal, easiest, cheapest	no specular, no shadow, noise relate to four light system
Four Light System	color-accurate diffuse albedo, more accurate surface normal,	no specular, no shadow
Linear Light System	Spatially varying specular, color-accurate diffuse albedo, high resolution surface normals, specular albedo, specular roughness fore each pixel, highly specular reflection, translucent material	no shadow
Laser Scanning System	surface normal	no diffuse color
Diffuse System	color accurate	no shadowing effect

Each system has its own advantage and disadvantage and another format summary is shown in Table 3.2.

Table 3.2: *Summary of systems comparison.*

System	Color Accuracy	Surface Normal	Spatially Varying BRDF	Height Map
RTI	low	yes	no	no
Conventional System	high	no	no	no
Soft-box System	high	no	no	no
Three-Light System	high	yes	no	no
Four-Light System	high	yes	no	no
Linear Light System	high	yes	yes	no
Laser Scanning System	low	no	no	yes
Diffuse System	high	no	no	no

Chapter 4

Experimental

4.1 Experiment I - Survey on Digitization Issues of Physical Properties of Paintings

Surface properties of paintings are important when photographing a piece of artwork so that the aesthetic feelings produced by the painting can be perceived in the image. Capturing all the surface properties of paintings is not easy; therefore, understanding what factors are most important when reproducing artwork is critical. The accurate reproduction of color is usually the primary goal of current workflows of fine art reproductions in museums and galleries. However, the capture of the texture, strokes, and shadows on the paintings has received more and more attention. A survey was conducted to better understand:

(1) the important parameters influencing the digital reproduction of artwork,

(2) how artwork reproductions can be best evaluated, and

(3) the usefulness of a real-time painting viewer that allows more interactive experience with the artwork by changing the viewing and lighting angles.

4.1.1 Survey Design (Hosted by SurveyMonkey®)

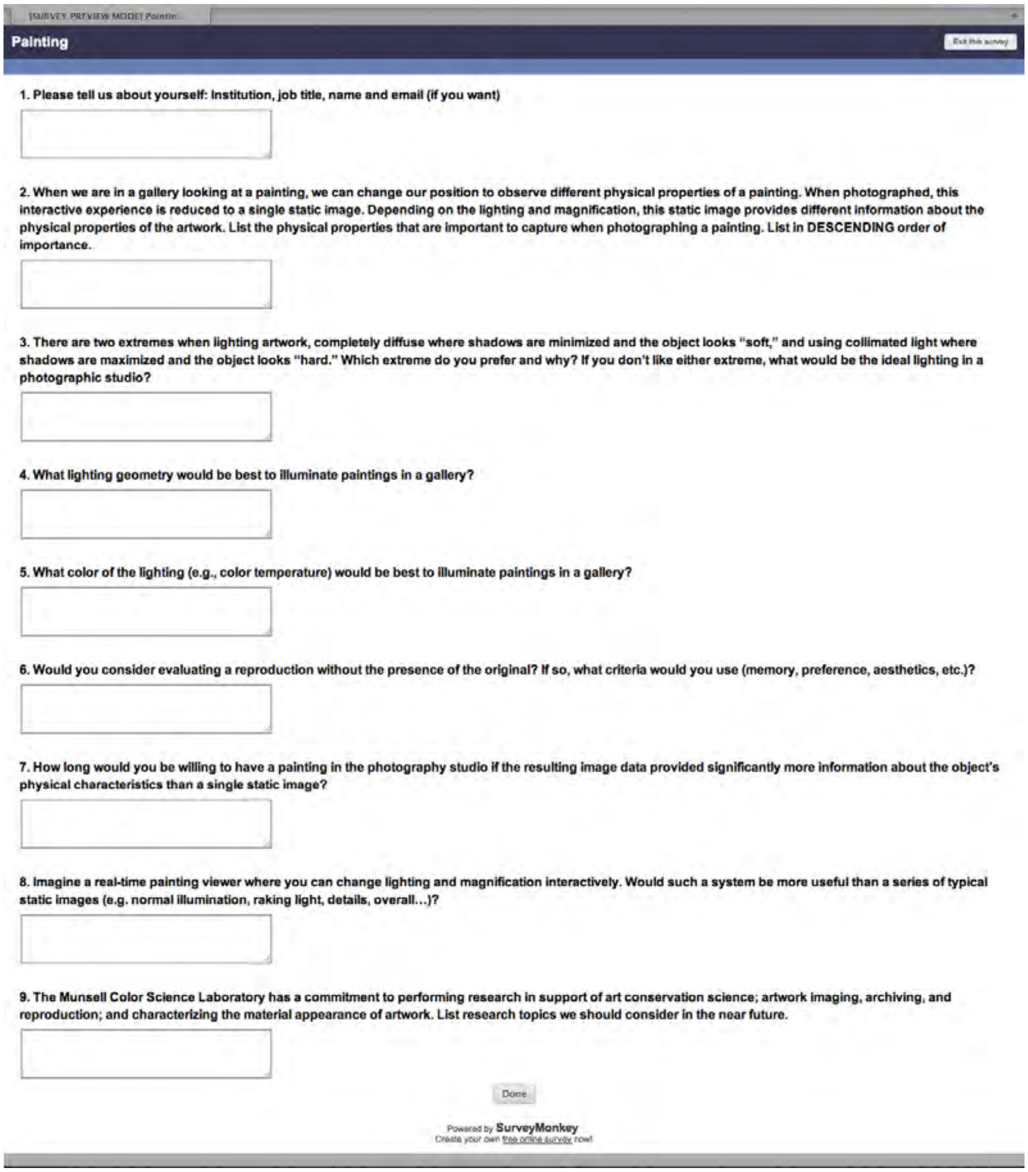
Nine questions were designed as shown in Fig. 4.1 to better understand the physical properties of paintings that are of great importance for reproduction. The questions can be categorized into three groups:

(1) important surface properties of the painting when reproducing artwork,

(2) lighting geometry and color to illuminate artwork in museum galleries, and

(3) the usefulness of a real-time painting viewer.

The questions were designed to be clear with a minimum of bias to the audience, experts working in the field of fine art reproductions. In order to engage the respondents, the questions were designed to be answered within 5-15 minutes. The survey was hosted on SurveyMonkey®from November 30th, 2011 to February 5th, 2012. The survey link was sent to colleagues of R. S. Berns, via email link and through the ImageMuse List serve mailing list (greater than 200 museums). Twenty-three respondents answered the survey. A screenshot of the survey questions is shown in Fig. 4.1. This survey was able to represent some professional interest, however, more respondents can be included in future.



Painting

Exit this survey

1. Please tell us about yourself: Institution, job title, name and email (if you want)

2. When we are in a gallery looking at a painting, we can change our position to observe different physical properties of a painting. When photographed, this interactive experience is reduced to a single static image. Depending on the lighting and magnification, this static image provides different information about the physical properties of the artwork. List the physical properties that are important to capture when photographing a painting. List in DESCENDING order of importance.

3. There are two extremes when lighting artwork, completely diffuse where shadows are minimized and the object looks "soft," and using collimated light where shadows are maximized and the object looks "hard." Which extreme do you prefer and why? If you don't like either extreme, what would be the ideal lighting in a photographic studio?

4. What lighting geometry would be best to illuminate paintings in a gallery?

5. What color of the lighting (e.g., color temperature) would be best to illuminate paintings in a gallery?

6. Would you consider evaluating a reproduction without the presence of the original? If so, what criteria would you use (memory, preference, aesthetics, etc.)?

7. How long would you be willing to have a painting in the photography studio if the resulting image data provided significantly more information about the object's physical characteristics than a single static image?

8. Imagine a real-time painting viewer where you can change lighting and magnification interactively. Would such a system be more useful than a series of typical static images (e.g. normal illumination, raking light, details, overall...)?

9. The Munsell Color Science Laboratory has a commitment to performing research in support of art conservation science; artwork imaging, archiving, and reproduction; and characterizing the material appearance of artwork. List research topics we should consider in the near future.

Done

Powered by SurveyMonkey
Create your own free online survey now!

Figure 4.1: *Screen shot of the survey.*

4.1.2 Questionnaire

The questions are listed in Table 4.1:

Table 4.1: *The questions in the survey.*

Number	Question
1	Please tell us about yourself: Institution, job title, name and email (if you want).
2	When we are in a gallery looking at a painting, we can change our position to observe different physical properties of a painting. When photographed, this interactive experience is reduced to a single static image. Depending on the lighting and magnification, this static image provides different information about the physical properties of the artwork. List the physical properties that are important to capture when photographing a painting. List in DESCENDING order of importance.
3	There are two extremes when lighting artwork, completely diffuse where shadows are minimized and the object looks "soft," and using collimated light where shadows are maximized and the object looks "hard." Which extreme do you prefer and why? If you don't like either extreme, what would be the ideal lighting in a photographic studio?
4	What lighting geometry would be best to illuminate paintings in a gallery?
5	What color of the lighting (e.g., color temperature) would be best to illuminate paintings in a gallery?
6	Would you consider evaluating a reproduction without the presence of the original? If so, what criteria would you use (memory, preference, aesthetics, etc.)?
7	How long would you be willing to have a painting in the photography studio if the resulting image data provided significantly more information about the object's physical characteristics than a single static image?
8	Imagine a real-time painting viewer where you can change lighting and magnification interactively. Would such a system be more useful than a series of typical static images (e.g., normal illumination, raking light, details, overall...)?
9	The Munsell Color Science Laboratory has a commitment to performing research in support of art conservation science; artwork imaging, archiving, and reproduction; and characterizing the material appearance of artwork. List research topics we should consider in the near future.

4.2 Experiment II - Psychophysical Evaluation

The intent of this experiment was to evaluate the performance of different systems that can measure the total appearance of art paintings. The psychophysical forced-choice paired comparison method was used and observers were introduced to choose one image between two different images compared with the illuminated original painting, the selection criterion based on four different questions. Those four different questions were generated considering the responses to the questionnaire.

4.2.1 Experimental Setup

The visual experiment was designed to enable observers to choose images between two different techniques compared with the illuminated original painting. The real painting was centered against an achromatic gray background (30% gray) and illuminated under simulated daylight using a Kodak CAROUSEL 5600 projector with two color temperature blue (CTB) filters #202 mounted in a slide. The light source's spectral power distribution (SPD) was measured using a Photo Research PR655 telespectroradiometer and aiming the PR655 toward pressed PTFE, placed at the object plane, the results plotted in Fig. 4.2. The SPD is typical of filtered incandescent, quite smooth.

The image pairs were displayed on a 30” Apple Cinema HD display with a resolution of 1920$\times$1200 pixels. The display was configured to use its native gamma and white point in the Apple ColorSync Utility. The nominal values were $\gamma = 2.2$ and D65 white point. Its SPD was also measured using the PR655, plotted in Fig. 4.2 . Since this display uses a fluorescent back light, its SPD is not smooth, but spiky. The chromaticities, luminance, and correlated color temperature (CCT) are listed in Table 4.2.

Because the PR655's accuracy was unknown and there was high demand for its use within the Munsell Color Science Laboratory, the decision was made to use a Minolta Chroma Meter CS-100A telecolorimeter. (In fact, it was later discovered that the PR655 had a 1.2nm shift towards longer wavelengths.) In the ColorSync Utility, the display's "brightness" was adjusted so that the maximum digital counts [255,255,255] (controlled using Matlab) equaled measurements of the pressed PTFE 106 cd/m^2. Comparisons of the hard- and soft-copy "whites" are listed in Table 4.2. Although the chromaticities were not identical, the difference in CCT was only 39. Because the diffuse albedos were identical for all the systems except the RTI system that was not color managed, the visual task was short-term memory matching where an observer was situated such that the painting and display would not be viewed simultaneously using binocular vision, and the current for the projector was not regulated, further calibration was not carried out.

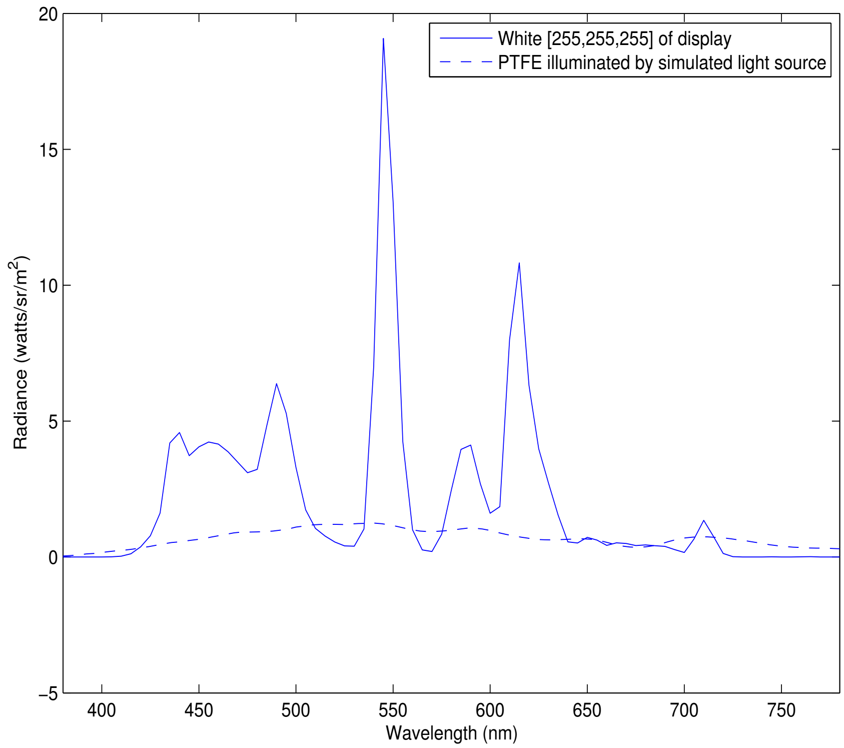


Figure 4.2: *Spectral power distribution of white measured by PR655.*

Table 4.2: *Colorimetry values of hard/soft copy displays measured by Chroma Meter CS-100A and PR 655.*

		Chroma Meter CS-100A				PR655			
		Y (cd/m^2)	x	y	CCT	Y (cd/m^2)	x	y	CCT
Hard copy	PTFE	106	0.317	0.383	6057	105.1	0.3144	0.3859	6144
Soft copy	White [255, 255, 255]	106	0.320	0.347	6096	105.4	0.3145	0.3458	6306

Twenty-five observers participated in the paired comparison experiment. Each observer was asked to make a choice for each pair of images based on the four questions listed in Table 4.3. The observers were seated 59 cm away from the setup. The real painting and image pairs were located at the same horizontal level as shown in Fig. 4.3, and the experiment was executed in a dark room.

Table 4.3: *Question list from psychophysical experiment.*

No.	Question
A	Which image looks most like the real painting?
B	Which image best conveys the painting's gloss/shininess?
C	Which image best conveys the painting's texture?
D	Which image best conveys the painting's color?

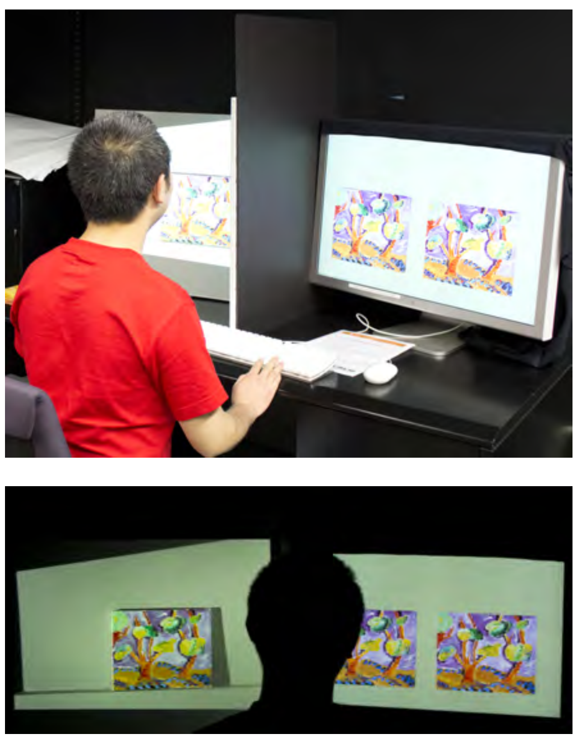


Figure 4.3: *Experimental setup used for the visual experiment.*

4.2.2 Experiment Framework

The functions to control the experiments were written in MATLAB. To carry out the experiments properly, a database containing paired comparison images had to be established first. The database was created as a four-dimensional cell element in MATLAB for easy indexing. The first dimension indicated the system index, the second indicated the geometry index, the third dimension was the painting set sequence, and the fourth dimension represented the number of the section. The entire experiment was made of four sections. In each section, a `loadimg` function was written to properly read in the images and sample them to fit within the screen. Only the images used in the pair comparison experiments were loaded in the database in order to save memory and increase performance.

Stimulus pairs also required an index to record which stimuli were presented to the left and the right panels for the comparison. We linearly indexed each image for simplicity. For example, given the database with n systems, m geometries and p paintings, the kth painting taken at the jth geometry using the ith system will have a linear index I as

$$I = (n \times m) \times (k-1) + (j-1) \times n + i. \tag{4.1}$$

For each painting set, if given n systems, $\frac{n\times(n-1)}{2}$ stimuli pairs must be generated and the left stimulus and right stimulus should be randomly interchanged in each pair. MATLAB internal function `randperm` was used for this purpose. A `GenStimSeq` function was written to generate the pair sequences, and the output of this function was a CSV file containing the trial number, left stimulus and right stimulus number as indexed by Eq. 4.1.

For each section of the experiment, the database was created individually and then merged to a four-dimensional cell matrix. The matrix was named `data` and was assigned as a read-only global variable. This allowed the matrix to remain in memory during the experiment; in this way, we reduced the waiting time for each session of the experiment. The pair sequence CSV files were also generated individually in correspondence with the session number.

Next, `RunExperiments` function was written to conduct the experiment. It was aimed to display the image pairs and let the observers choose the preferred image according to the asked questions by using the left/right arrows. First, the function asked the observers for their subject ID and experiment ID; this information will be useful to export and discriminate results. Next, a question popped up on the full-screen window indicating the desired feature for the observers to judge. A screenshot of such a question is shown in Fig. 4.4. Then in each section, the stimuli sequence generated by `GenStimSeq` was read in and the image stimuli were also read in. The experimental interface is shown in Fig. 4.5.

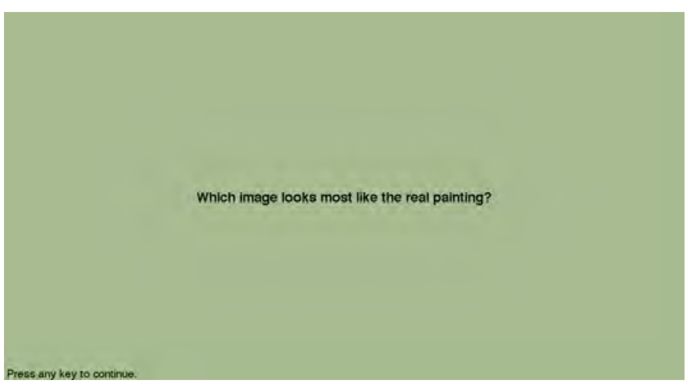


Figure 4.4: *Screen shot of the question interface. The annotation is shown at the left bottom corner of the screen.*

Figure 4.5: *Screen shot when running RunExperiment. The annotation is shown at the left bottom corner of the screen.*

In the data-collection procedure, the figure window was maximized by setting the figure window as large as the screen size. An annotation text box (`annotation` function in MATLAB) was created on the left bottom corner to display useful information such as the asked question. The function then displayed the two stimuli pairs in sub figures. The `subimage` function (internal to MATLAB) was used to display the image in sub figures that would automatically adjust the image size without changing the figure window. Then, `set` and `get` commands were used to adjust the images to be on a fixed horizon as with the actual displayed painting. After the images were displayed, a `while` loop was constructed and `waitforbuttonpress` collected the user input. The loop would *only* end if a left arrow key or a right arrow key was captured. The `get(fig,'currentcharacter')` was used to capture the keyboard stroke. The character was converted to an integer type for comparison (ASCII code); if an ASCII code of 28 was detected, then the user input was "left arrow" and ASCII code of 29 indicated a "right-arrow" input. The user input was then recorded using 0 for left and 1 for right. After all the sequences were shown, the recorded data were stored in a unique folder named with he subject ID and experiment

ID. In this folder, the results for each section were stored in separated text files named with the question number and the corresponding part number.

4.2.3 Stimuli Generation

To perform the psychophysical experiment, a fixed geometry was chosen for each of these methods. The angle between the plane of a painting and the illuminating light was chosen to be 60° to represent similar image capture to conventional and soft-box illumination systems. The RTI data was generated by RTIViewer using tree.*ptm* file and the spotlight was moved to 60^o shown in Fig. 4.6. Linear, three-light and four-light systems were set up in the MCSL and the database (Ashbaugh et al., 2009) was created in-house; the 60° image was also generated from *ArtViewer* shown in Fig. 4.7. The software, ArtViewer, was used to render images for specific geometries and for studio lighting (Berns et al., 2012b). In three-light and four-light systems, a uniform bi-directional reflectance distribution function (BRDF) model (Ward, 1992)(Cook & Torrance, 1982) fitting 600 uniform BRDF characteristic samples (Berns, 2013) was used. ArtViewer permitted the user to adjust the BRDF parameters and only specular ρ_s and roughness ρ_r were fine adjusted within 5% of the default setting to match the conventional as close as possible because of spatially-varying gloss. The laser scan data were collected from Arius3D a commercial laser scanning system. Its output data were point cloud data and these data were converted to a hight map processed by Darling based on research by Darling and Ferwerda (Darling & Ferwerda, 2012); color information came from the four-light system. The raw point cloud data from the scan (5.3 million points) was interpolated to a regular grid to create a height field for the surface. A surface normal map and set of horizon maps (Sloan &

Cohen, 2000) were calculated from the height field using custom software. The surface geometry was manually aligned with diffuse color maps and specular reflectance maps from the four-light system. The images were rendered in a custom OpenGL-based rendering engine (Darling & Ferwerda, 2012) using point lighting. The software provides capabilities to render surface texture using normal maps, self-shadowing using horizon mapping, and specular reflections using the Ward model. Table 4.4 gives the details about these reproduction systems.

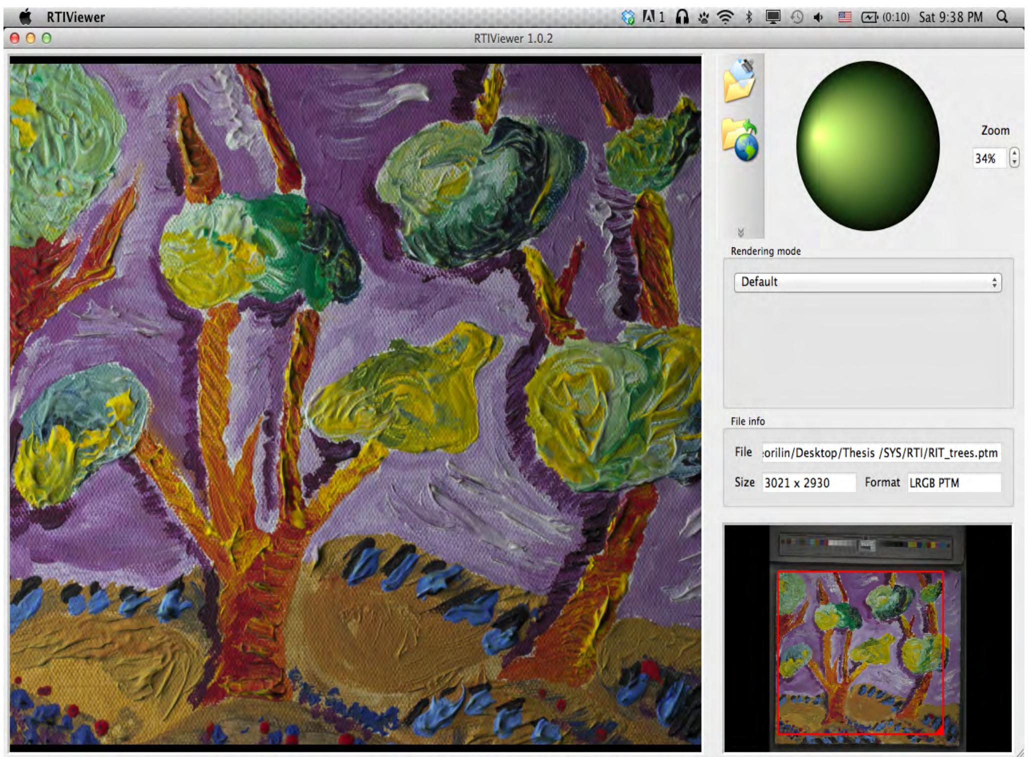


Figure 4.6: *Screenshot of RTIViewer.*

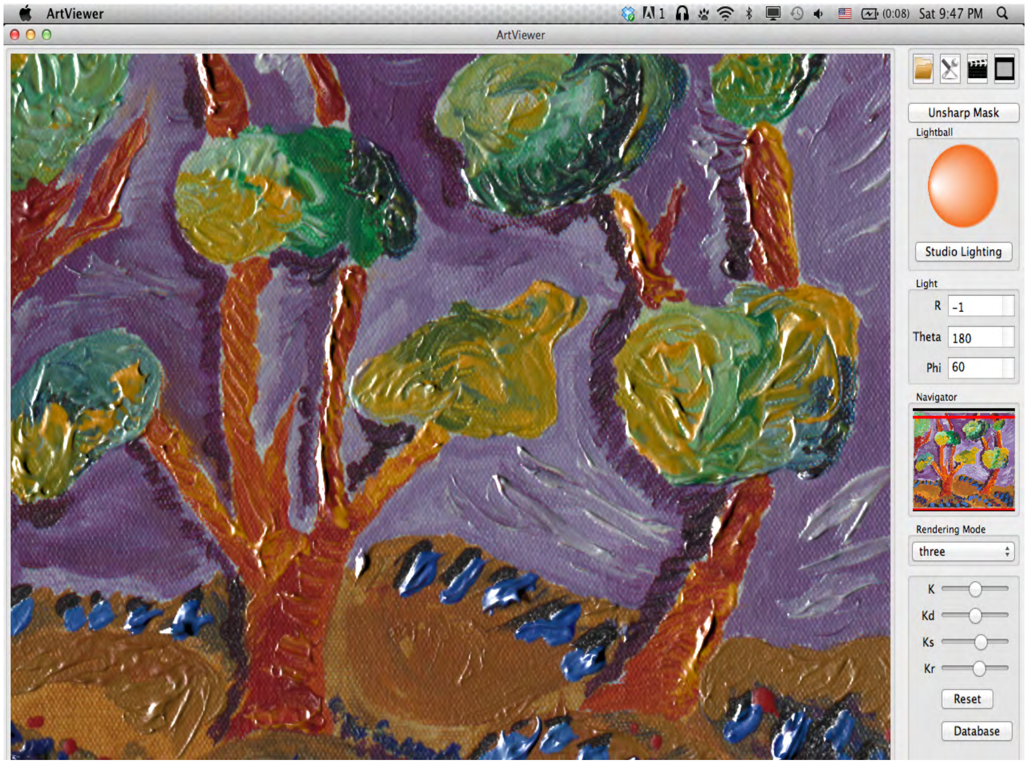


Figure 4.7: *Screenshot of ArtViewer.*

Table 4.4: *Reproduction systems.*

Method	Description
Conventional	Digital reproductions were made using DSLR (Canon 5D) under a directional Broncolor Pulso G 1600 J strobe.
Linear	Digital reproductions were made using DSLR (Canon 5D) under a linear light source (fluorescent tube). A filter wheel housing the dual-RGB filters was fixed to the camera. A B&H a linear polarizer was attached to the front of the filter wheel. Experimental setup is shown in Fig. 3.8. The color information cannot be collected using the Linear system, and therefore, it was obtained from the four-light system.
Three	Digital reproductions were created using DSLR (Canon 5D) under three Broncolor Pulso G 1600 J strobes from different directions. A filter wheel housing the dual-RGB filters was fixed to the camera. A B&H linear polarizer was attached to the front of the filter wheel. Experimental setup is shown in Fig. 3.2.
Four	Digital reproductions were created using DSLR (Canon 5D) under four Broncolor Pulso G 1600 J strobes from different directions. A filter wheel housing the dual-RGB filters was fixed to the camera. A B&H linear polarizer was attached to the front of the filter wheel. Experimental setup is shown in Fig. 3.3.
RTI	Digital reproductions were created using the Reflectance Transformation Imaging (RTI) system.
Soft-box	Digital reproductions were created using DSLR (Canon 5D) under diffuse (conventional soft-box) light sources.
Laser	The surface normal of digital reproductions were created using a commercial laser-scanner software. The color information was obtained from the four-light system.
Diffuse	The color information is generated by averaging four diffuse albedo images of the four-light system.

4.2.4 Data Processing

All the observer data were collected in one folder and were input using the `dir` function. The function lists all the files that follow a given pattern so that one could use `fopen` to open the files successively.

When one data file for a specific subject and experiment ID was read in, an observer confusion matrix of size 7×7 (in this case) was created. In fact, the function was able to automatically calculate the dimension by finding the maximum in the left_stimuli column. Given an initial value of all zeros, the (i, j) value of the confusion matrix was incremented for a comparison between stimulus i and j with j being chosen by the observer for each trial. The functions to perform these routines were `data2confmat` (handles confusion matrix for each session) and `createmat` (summarizing all sessions).

Chapter 5

Analysis and Discussion

5.1 Experiment I - Survey on Digitization Issues of Physical Properties of Paintings

The following sections review the information gathered from the twenty-three respondents of the digitization survey.

5.1.1 Respondents' Survey Data

Q1. Please tell us about yourself: Institution, job title, name and email (if you want).

Question 1 collated the backgrounds of the respondents, summarized in Fig. 5.1. Most were heads or directors of imaging services, artists, or photographers.

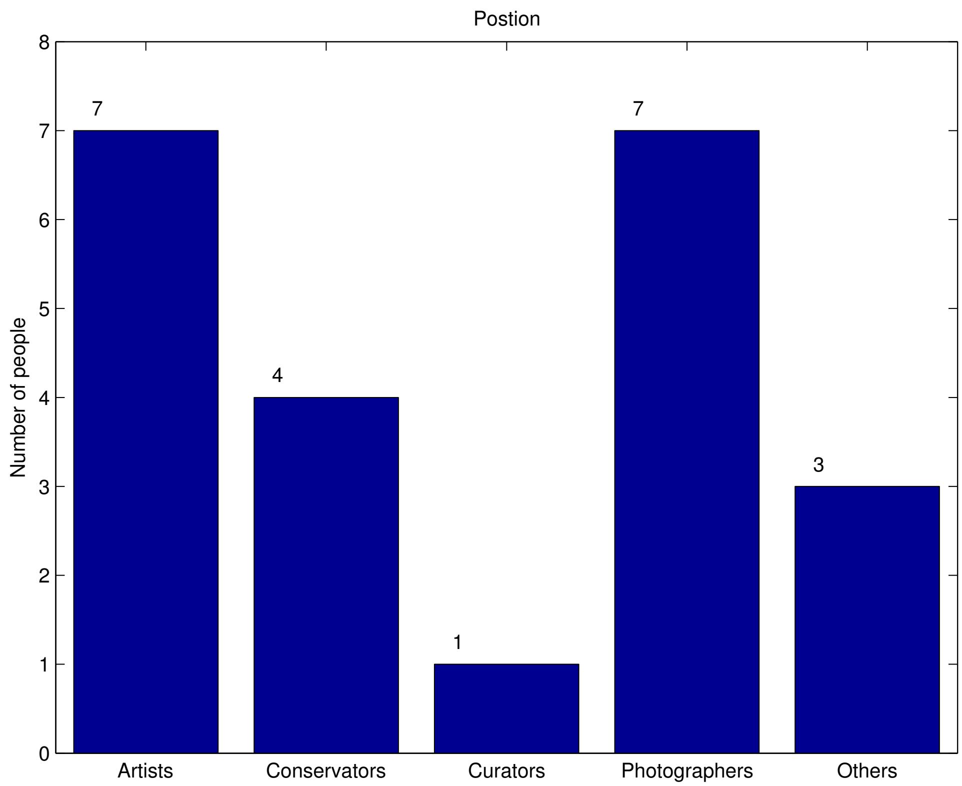


Figure 5.1: *The background of 23 respondents. The percentage value is the number of respondents in that group dividing the total umber of respondents (23). .*

Q2. When we are in a gallery looking at a painting, we can change our position to observe different physical properties of a painting. When photographed, this interactive experience is reduced to a single static image. Depending on the lighting and magnification, this static image provides different information about the physical properties of the artwork. List the physical properties that are important to capture when photographing a painting. List in DESCENDING order of importance.

Question 2 was designed to understand what physical properties of the artwork are important when imaging.

The answers by respondents are summarized in Table 5.1. The responses are categorized into three groups: surface properties, color, and other factors (e.g., size). Most respondents mentioned surface properties including texture (seventeen respondents), surface reflectance (four respondents), minimum specular highlight (four respondents), and material appearance (two respondents). Texture was discussed most often, including paint strokes, canvas, media, sufficient details, tears and losses, relief, and gloss/matte in their answers. Color (e.g., accurate color reproduction and tonal relationship) was listed by seventeen respondents. Other factors included size, squareness and sharpness. In summary, color and texture were the two most important characteristics reported by respondents.

Table 5.1: *Summary of important physical properties of the artwork for total respondents.*

Important physical properties of the artwork			
Category	surface properties	color	other concerns
	texture (17)	color (17)	squareness (4)
	surface reflectance (4)	tone (2)	size (3)
	minimum specular highlight (4)		sharpness (2)
	material (2)		

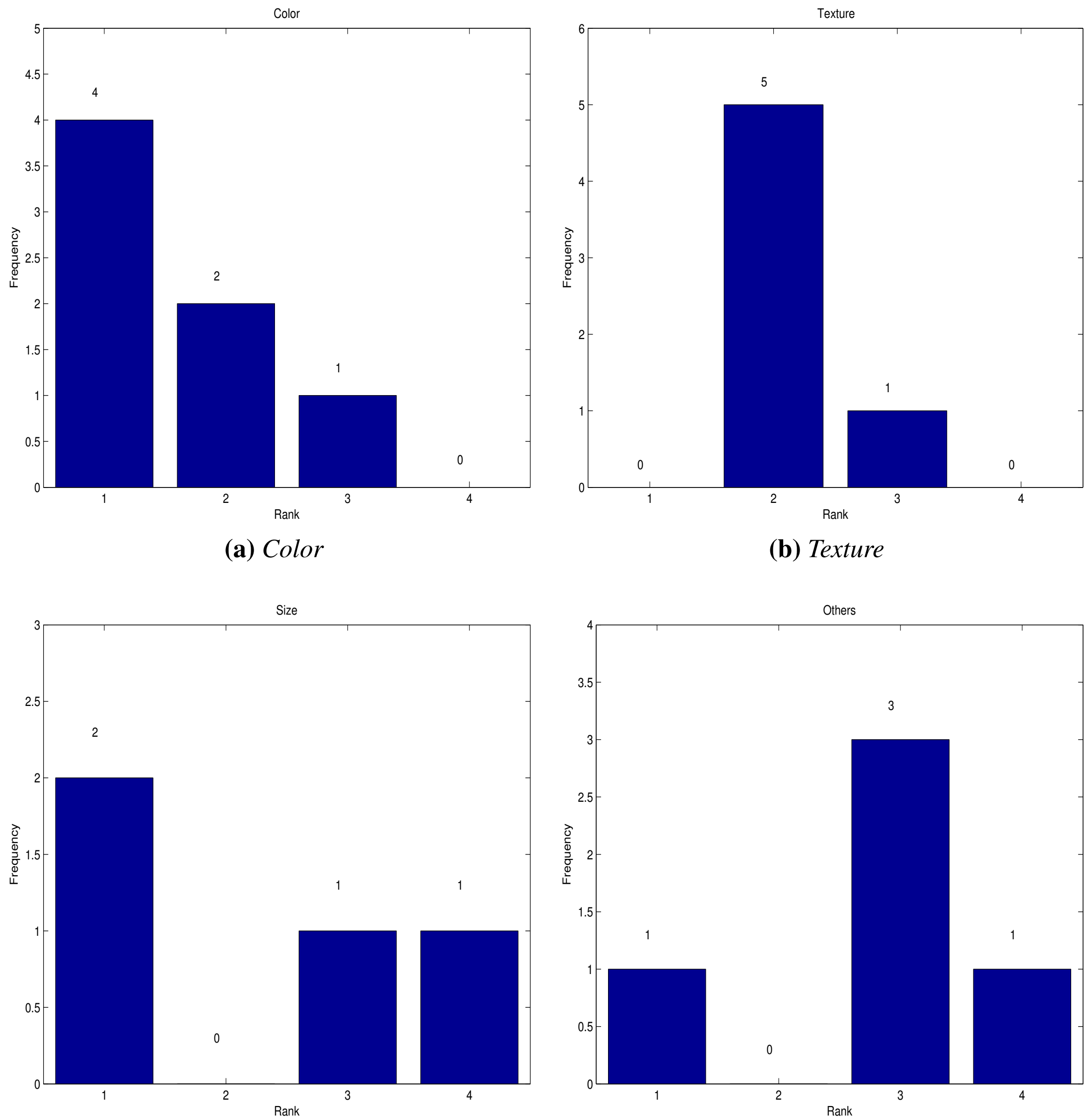
An analysis was also made based on respondents' background. Five groups of respondents were identified in Fig. 5.1: (1) artist [7], (2) conservator [4], (3) curator [1], (4) photographer [7], and (5) others [3]. (The number in square brackets is the number of respondents in that group.) For artists, the properties that are of greatest importance when photographing a piece of artwork are listed in Table 5.1. In Table 5.1, the rank is the order of properties mentioned by artists. The higher the rank, the more important the property is by the respondent. The answers from seven artists are shown in the seven columns in

Table 5.1.

Table 5.1: *The properties that are of great importance when photographing artwork by seven artists. The row number is the artist index and the column number is the ranking order.*

Rank	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	size	color	color	composition	color	size	color
2	texture	texture	texture	color	texture	color	texture
3	color	material	min specular highlight	min specular highlight	size	squareness	
4	reflectance	size					

Table 5.1 can be visualized in Fig. 5.2. In Fig. 5.2 (a), color was mentioned by four artists as the most important property, by two artists as the second most important property, and by one artist as the third most important property. Given seven artists, four artists reported color to be the top property when reproducing the artwork. Texture was mentioned by five artists as the second most important characteristic. In addition, size was reported by four artists in Fig. 5.2 (c). Other characteristics such as composition, squareness, and minimizing specular highlight and reflectance were mentioned in Fig. 5.2 (d).

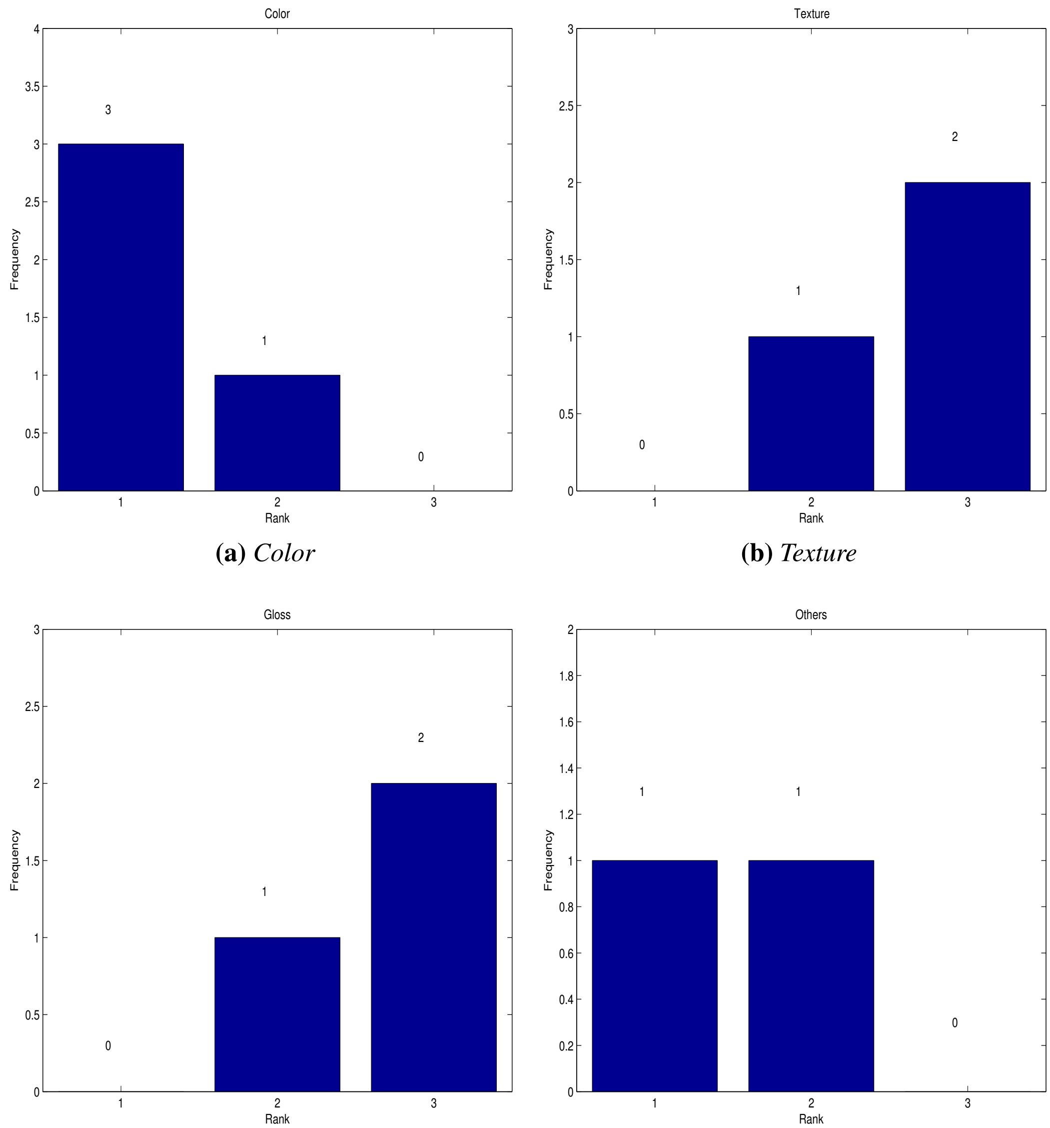


(a) *Color* **(b)** *Texture*

(c) *Size* **(d)** *Others*

Figure 5.2: *The most important properties to seven artists when photographing artwork. The results are grouped into color, texture, size and others. The x axis is the rank order while the y axis is the frequency of this property mentioned by respondents. For example, color was mentioned by four artists as the most important properties, another two artists as the second most important property, and one artist as the third most important property.*

Similar analysis was performed for conservators shown in Table 5.2 and Fig. 5.3.



(a) *Color* **(b)** *Texture*

(c) *Gloss* **(d)** *Others*

Figure 5.3: *The most important properties when photographing artwork by four conservators.*

Table 5.2: *The most important properties when photographing artwork by four conservators.*

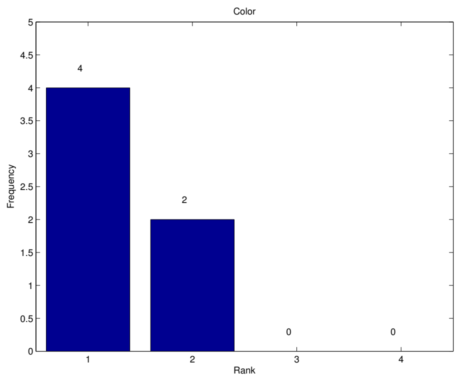
Rank	1	2	3	4
1	color	structural (tears, losses, cracking)	color	color
2	detail	color	gloss/matte	texture
3	texture	gloss/matte	texture	gloss/matte

In Fig. 5.3, three conservators reported color to be the single most important feature when photographing artwork. Texture and gloss were mentioned to be of similar importance, second to color.

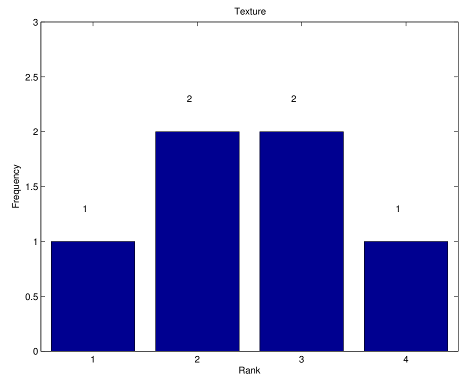
For photographers, the analyses are shown in Table 5.3 and Fig. 5.4. In Fig. 5.4, more than half of the photographers mentioned color as the most important characteristics when capturing artwork. Texture, details, and reflectance were reported to be critical as well. Other factors including squareness, minimizing specular reflection, and size were mentioned as well in Fig. 5.4 (e).

Table 5.3: *The most important properties when photographing artwork by seven photographers.*

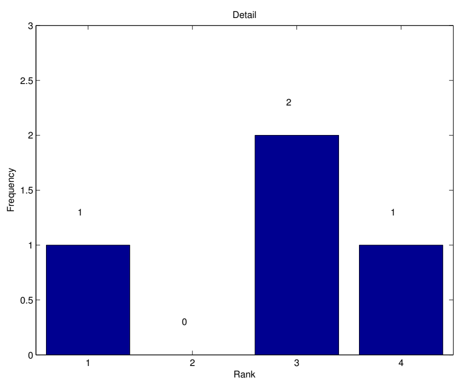
Rank	1	2	3	4	5	6	7
1	color	detail	color	texture	sharpness	color	color
2	tone	color	texture	reflectance	color	texture	squareness
3	texture	min specular highlight	detail	color	detail	reflectance	texture
4	gloss/matte			size	texture		detail



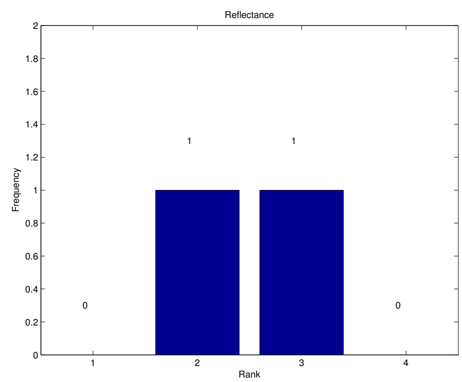
(a) *Color*



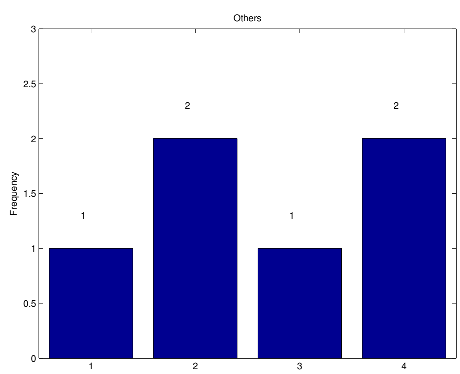
(b) *Texture*



(c) *Detail*



(d) *Reflectance*



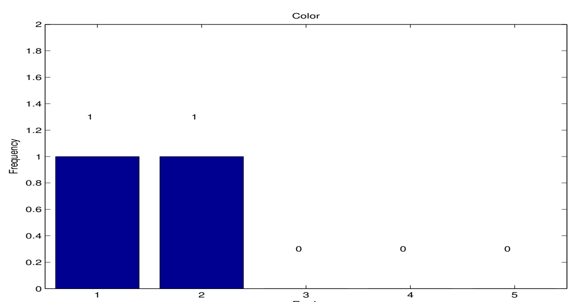
(e) *Others*

Figure 5.4: *The most important properties when photographing artwork by seven photographers.*

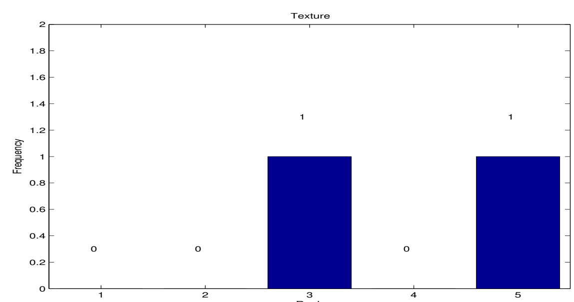
For other respondents (three respondents in total), the results can be found in Table 5.4 and Fig. 5.5. In Fig. 5.5, color and texture were mentioned to be the first and second most important properties when reproducing artwork. Other factors, such as minimizing specular reflectance, sharpness, and contrast are displayed as well in Fig. 5.5 (c).

Table 5.4: *The most important properties when photographing artwork by others.*

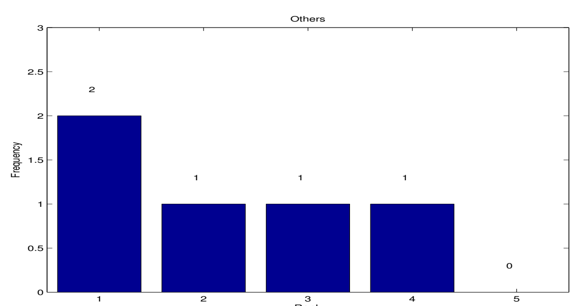
Rank	1	2	3
1	color	tone	min specular highlight
2	sharpness	color	
3	contrast	texture	
4	no field distortion		
5	texture		



(a) *Color*



(b) *Texture*



(c) *Others*

Figure 5.5: *The most important properties when photographing artwork by others.*

Only one respondent was in the curator group, and his answer is shown in Fig. 5.6. Surface texture and glossiness were mentioned to be the most important.

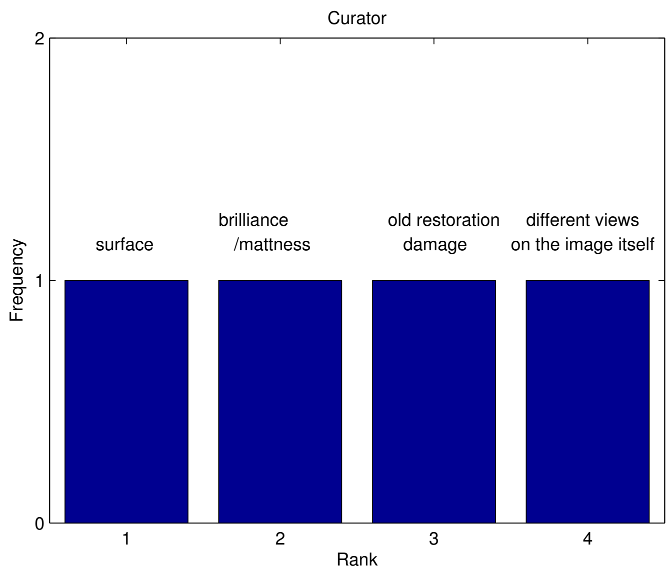


Figure 5.6: *The respondent of curator.*

Q3. There are two extremes when lighting artwork, completely diffuse where shadows are minimized and the object looks "soft," and using collimated light where shadows are maximized and the object looks "hard." Which extreme do you prefer and why? If you don't like either extreme, what would be the ideal lighting in a photographic studio?

Question 3 was aimed at understanding which extreme lighting system was preferred, directional lighting or diffuse lighting. Directional lighting is able to maximize shadows in the painting and to make the object look "hard." This lighting will also produce observable specular highlights. Diffuse lighting, on the other hand, minimizes the shadows and makes the object look "soft." The answers are shown in Fig. 5.7. Ten out of twenty-one respondents (two respondents skipped this question) believed that the use of directional or diffuse lighting depended on the painting. The other respondents generally preferred somewhere in between to either extreme lighting system. For artwork with smooth surfaces, soft lighting was preferred. While for paintings with rough surfaces, directional light was generally favored to reveal more surface details. However, no one preferred using the directional light alone.

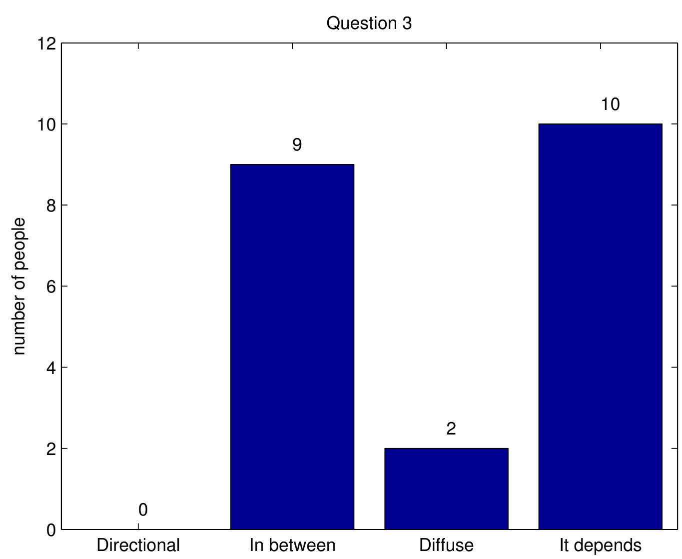
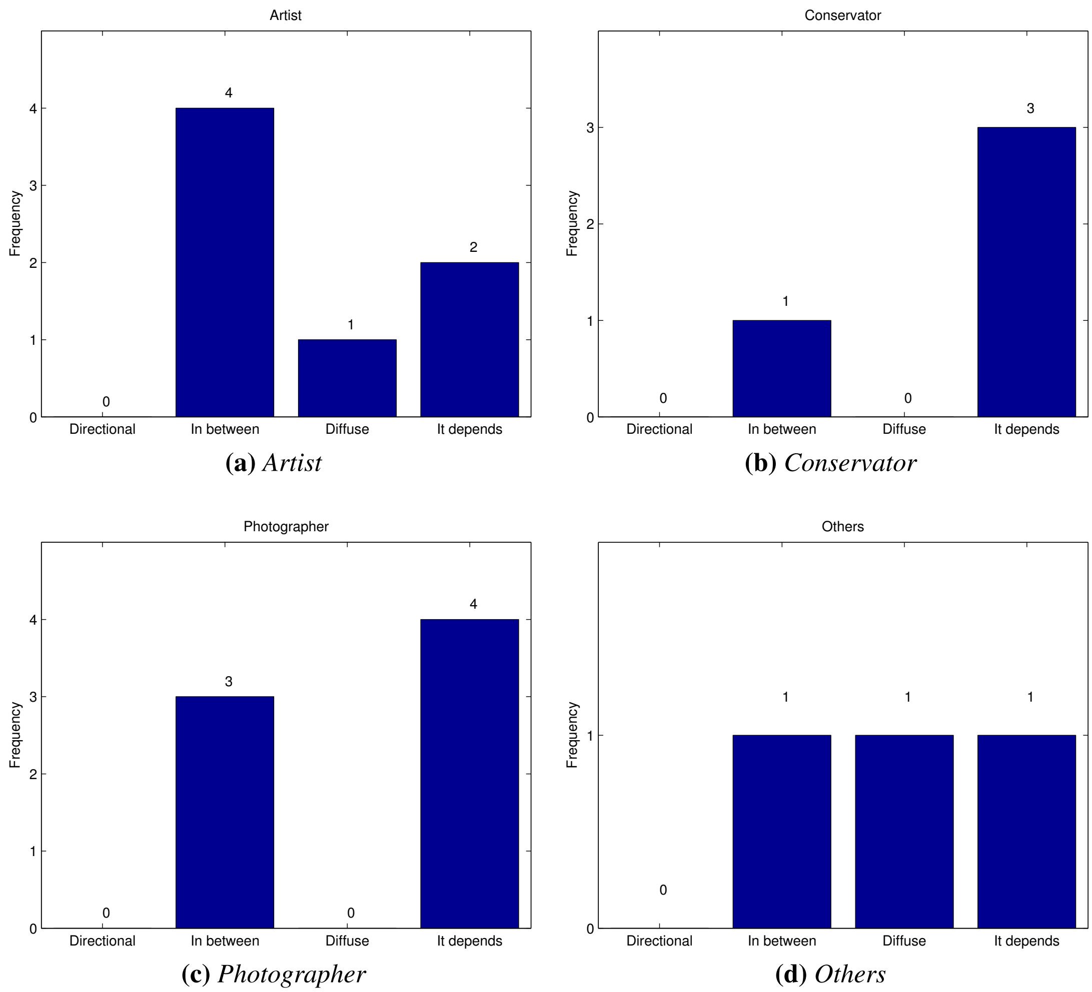


Figure 5.7: *The preference of directional or diffuse lighting system to light artwork by all respondents.*

The preference of diffuse or directional lighting to illuminate artwork may also depend on the background of the respondents. Therefore, an analysis of preferences was made based on respondents' occupations in Fig. 5.8.

In Fig. 5.8, artists preferred neither diffuse nor directional lighting overall. Instead, they wanted somewhere in between. For conservators and photographers, whether the lighting system in museums should be directional or diffuse depended on the painting.



(a) *Artist* **(b)** *Conservator* **(c)** *Photographer* **(d)** *Others*

Figure 5.8: *The preference of directional or diffuse lighting system to light artwork by respondents of different occupations.*

For the one curator, a combination of the two extremes is preferred: "for painting I prefer diffuse shadows but not completely, because then you lose 3 dimensionality."

Q4. What lighting geometry would be best to illuminate paintings in a gallery?

Question four investigated what lighting geometry was preferred in museums when illuminating paintings. Based on the answers in Fig. 5.9, diffuse lighting was preferred overall. Overhead diffuse lighting was mostly mentioned by respondents.

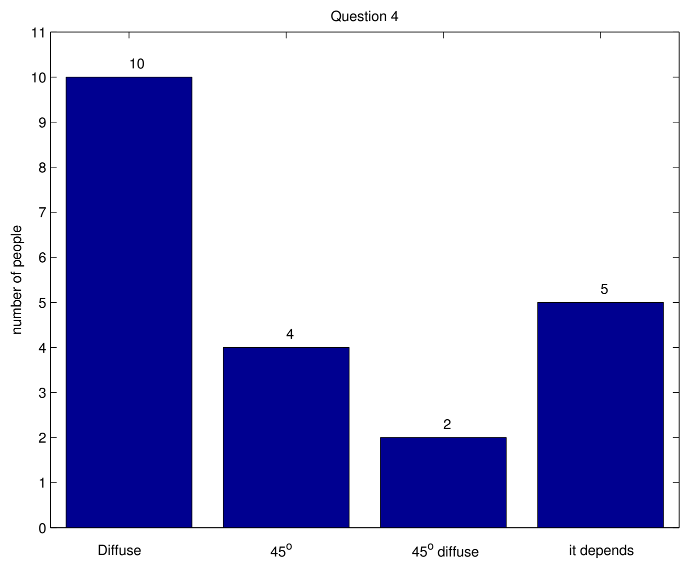
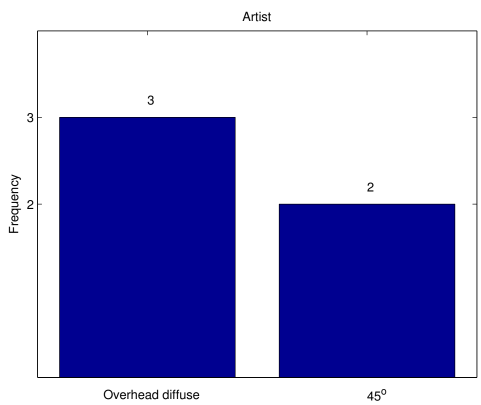
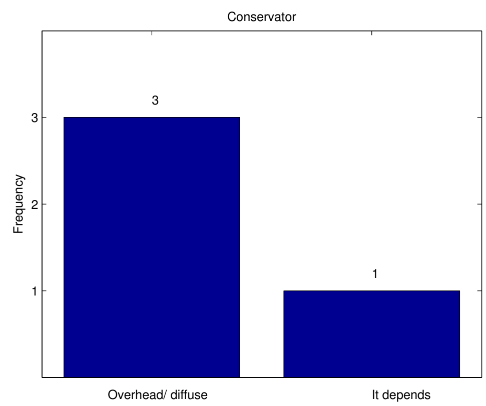


Figure 5.9: *The lighting geometry preferred to illuminate paintings by all respondents.*

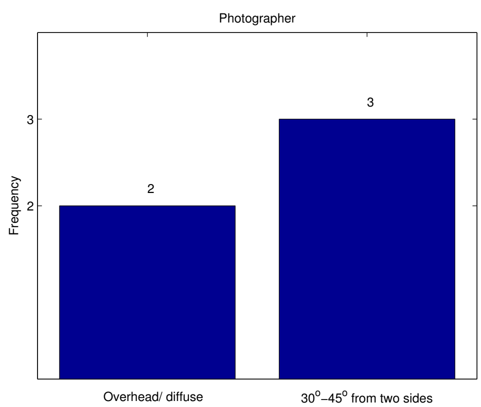
Analysis was further made based on respondents' positions in Fig. 5.10. In Fig. 5.10, artists generally preferred overhead diffuse lighting or lightings at 45-degree on both sides. Overhead diffuse lighting is used to minimize specular highlight on the artwork. Similar preference could be found for photographers as well. On the other hand, none of the four conservators mentioned 45-degree lighting in their responses. Instead, they generally preferred overhead or diffuse lighting to illuminate the artwork. The curator did not answer this question.



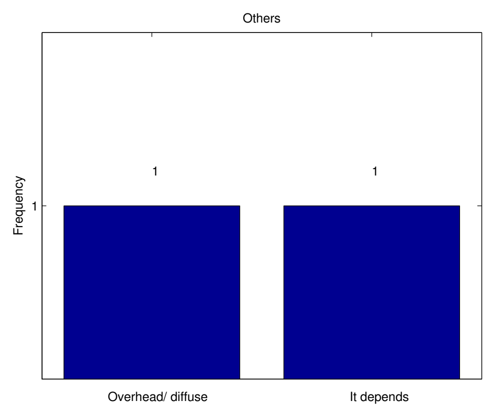
(a) *Artist*



(b) *Conservator*



(c) *Photograher*



(d) *Others*

Figure 5.10: *The best lighting geometry to illuminate paintings in a gallery by different groups of respondents.*

Q5. What color of the lighting (e.g., color temperature) would be best to illuminate paintings in a gallery?

This question determined what color of the lighting would be the best to illuminate paintings in a gallery environment. The answers are categorized in Fig. 5.11. Nine respondents preferred daylight ($\geq 5000\ K$), D50 and D65, while a similar number of respondents preferred lighting a lower CCT in the range of 3000 K $-$ 3500 K (e.g., Solux of 3500$^{\circ}K$ lighting). Three respondents thought the color of the lighting is dependent on the types of galleries, paintings, and applications.

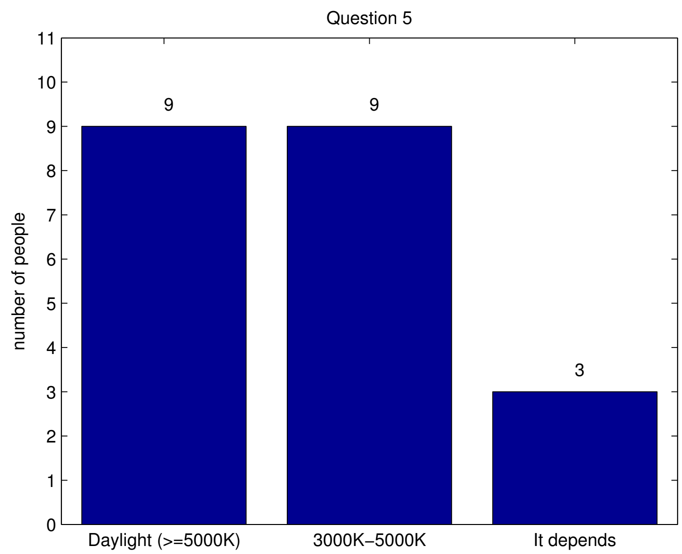
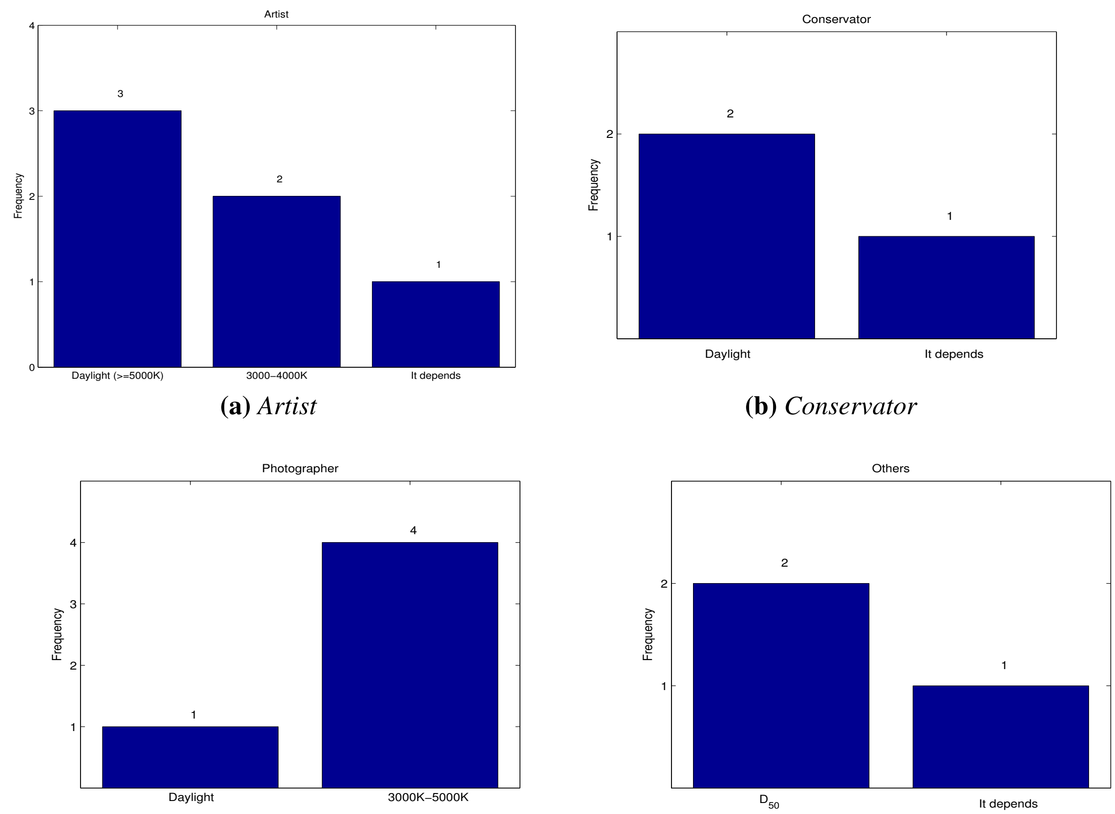


Figure 5.11: *The best color of lighting (e.g., CCT) to illuminate paintings in a gallery.*

For artists, the preferred CCT of the lighting varied widely from 3000K to 6500K. Photographers, on the other hand, generally preferred yellowish lighting, with CCT ranging from 3000K to 5000K as shown in Fig. 5.12 (c). A number of respondents mentioned 'daylight' in their answers, but the CCT of the daylight was not specified. For the curator, the color of lighting depended on the project and gallery. But in their gallery, light of 2800-3000K seemed fine.



(a) *Artist* **(b)** *Conservator*

(c) *Photographer* **(d)** *Others*

Figure 5.12: *The best color of the lighting (e.g., CCT) to illuminate paintings in a gallery by different groups of repondents.*

Q6. Would you consider evaluating a reproduction without the presence of the original? If so, what criteria would you use (memory, preference, aesthetics, etc.)?

Question 6 was aimed at understanding whether the reproduction should be evaluated with or without the presence of the original. With the original, observers are more likely to evaluate the reproductions based on how accurate the color and texture are reproduced. On the other hand, when the originals are not available, preference rather than accuracy may become more critical in evaluating the reproductions. The answers to the question are summarized in Fig. 5.13. Most respondents preferred having the original when evaluating reproductions. However, it was not always the case that the originals were available at their disposal when evaluating the artwork. Most respondents chose w/o the original' because the original was not available. Eight respondents believed that it was best to evaluate reproductions with the original, as preferences, aesthetics, and memory could be misleading when evaluating (the accuracy of) a reproduction. In addition, one respondent thought that the choice depends on the usage.

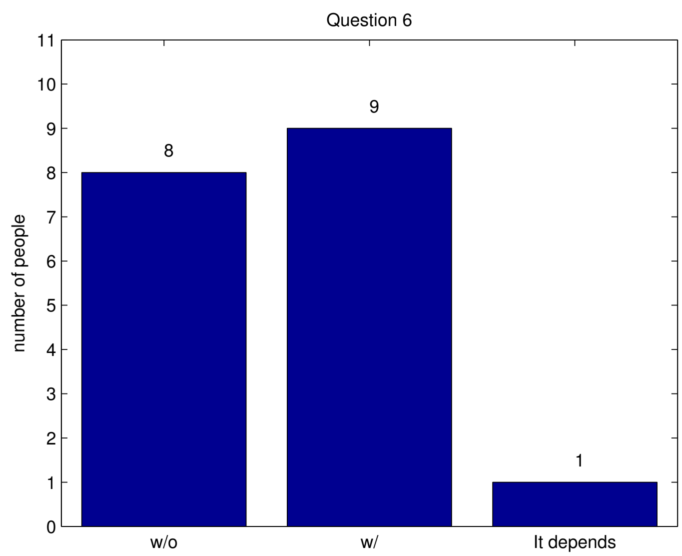


Figure 5.13: *The use of the original when evaluating the reproductions by all respondents. (w/: with the original; w/o: without the original)*

The responses are also evaluated based on the respondents' background. Most conservators insisted evaluating the reproductions with the presence of the original. On the other hand, artists were generally less critical of the availability of the original when assessing the image quality of the reproductions. The curator did not provide the answer for this question.

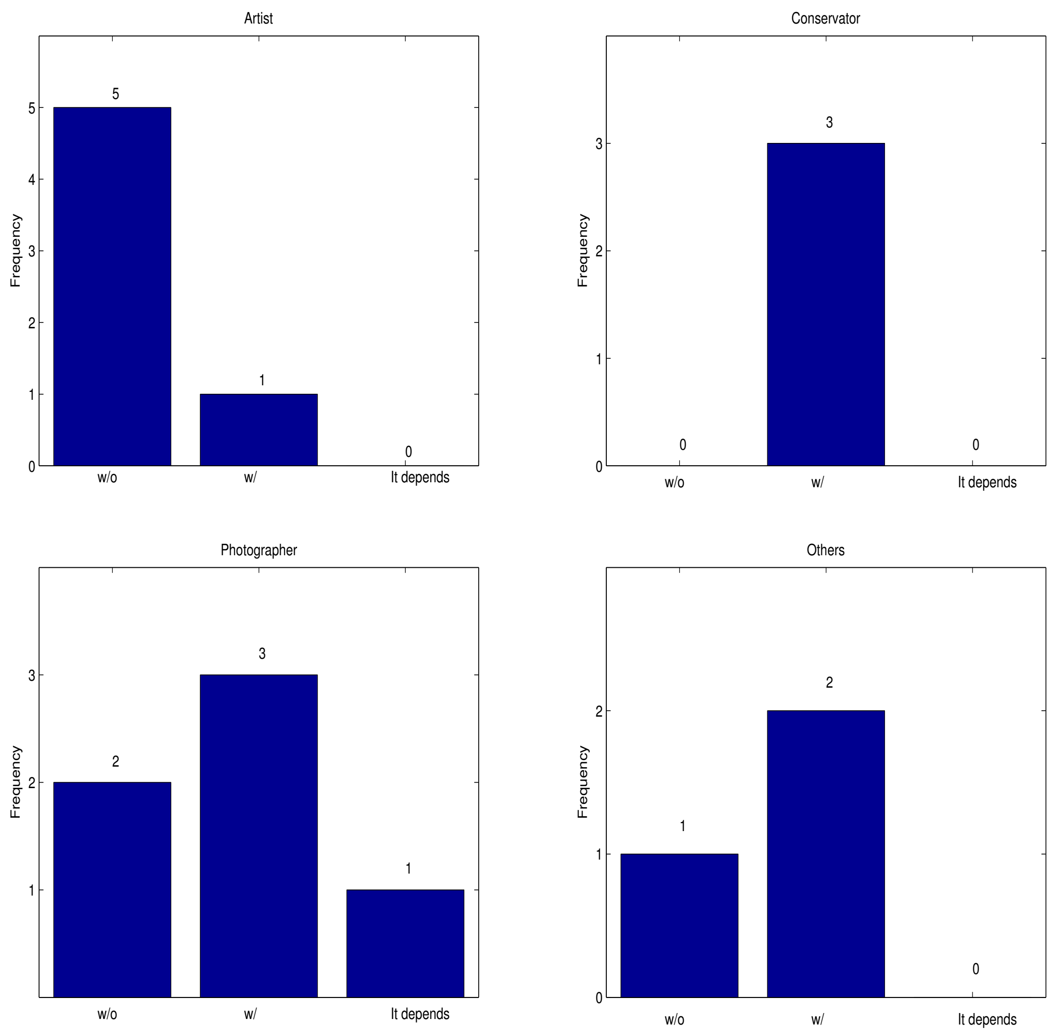


Figure 5.14: *The use of the original when evaluating the reproductions by different groups of respondents.*

Q7. How long would you be willing to have a painting in the photography studio if the resulting image data provided significantly more information about the object's physical characteristics than a single static image?

Question 7 was aimed at finding out how long respondents would be willing to spend collecting significantly more information of the painting in the photography studio. The answers are summarized in Fig. 5.15. Most respondents were not critical about the extra time needed to collect significantly more information, ranging from a few days to as long as it takes. Five respondents thought that it should depend on the purpose of the capture, materials used in the object, and the importance of the painting.

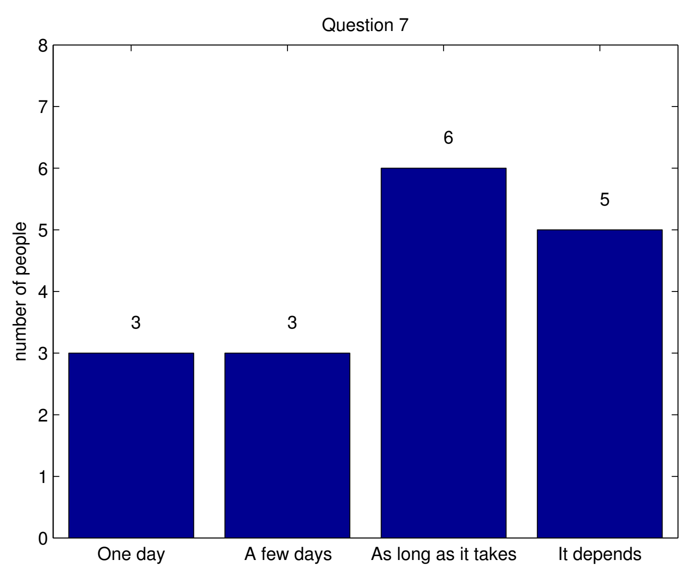
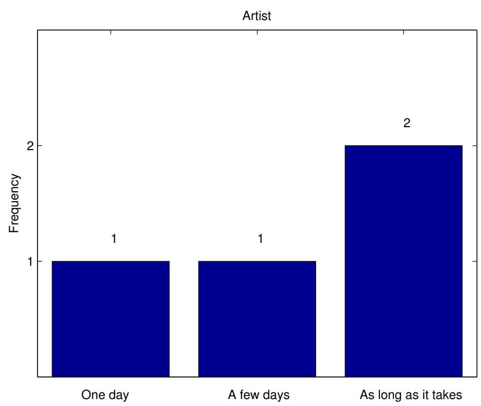
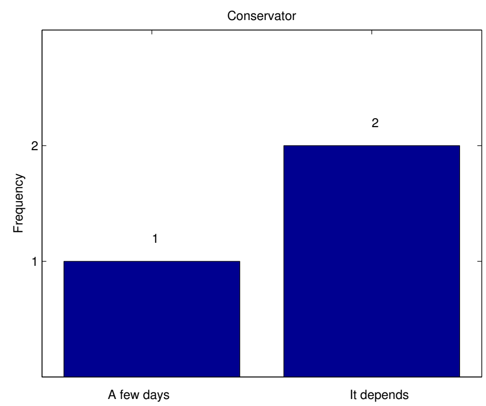


Figure 5.15: *The extra time that respondents are willing to spend collecting significantly more information of a painting in the photography studio.*

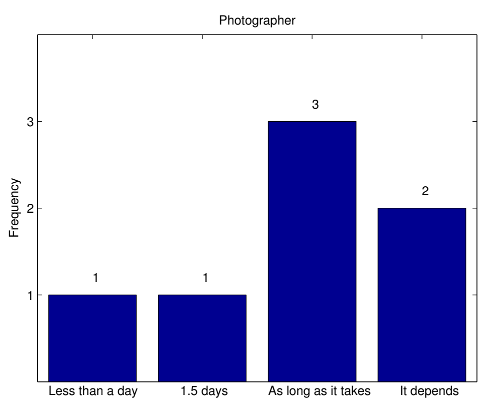
The analysis is also made based on the background of the respondents in Fig. 5.16. Artists and photographers were more lenient with the extra time used to collect additional information of the painting, as half of the respondents in both groups (artist and photographer) answered 'as long as it takes' when being asked the question. The curator thought that the time was dependent on the purpose of the reproduction (depending on what you want to know, one day).



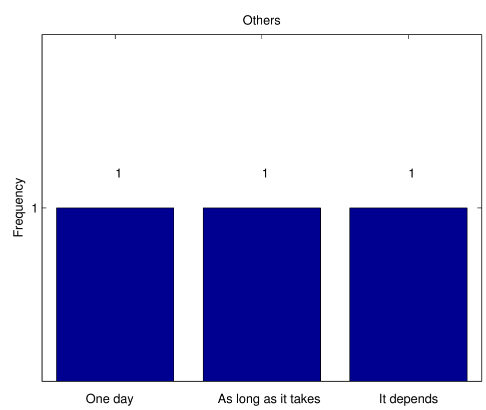
(a) *Artist*



(b) *Conservator*



(c) *Photographer*



(d) *Others*

Figure 5.16: *The extra time that respondents are willing to spend collecting significantly more information of a painting in the photography studio by respondents in different groups.*

Q8. Imagine a real-time painting viewer where you can change lighting and magnification interactively. Would such a system be more useful than a series of typical static images (e.g., normal illumination, raking light, details, overall...)?

Question 8 was aimed at understanding the attitude of a real-time painting viewer that can be used to change lighting and magnification interactively. The answers are categorized in Fig. 5.17. Most respondents agreed that it was an interesting and useful application to facilitate the understanding of the painting. Eight respondents believed that it depended on the painting, final destination and media, and applications. On the other hand, only one respondent was not so positive of the idea, believing that there was no substitute for being in front of the actual painting. In summary, most respondents were positive to the interactive experience with the artwork, despite concerns ranging from affordability to accuracy.

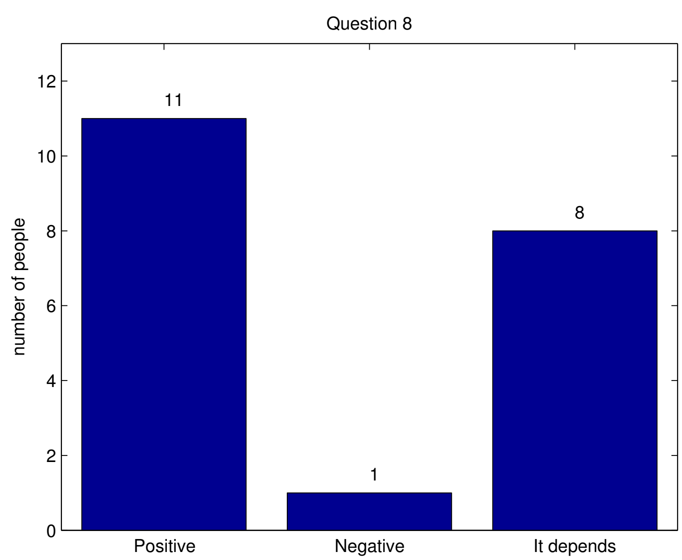
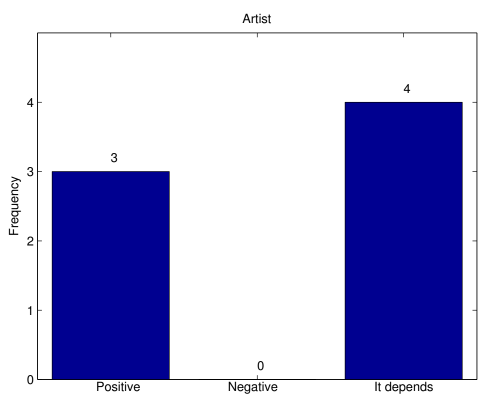
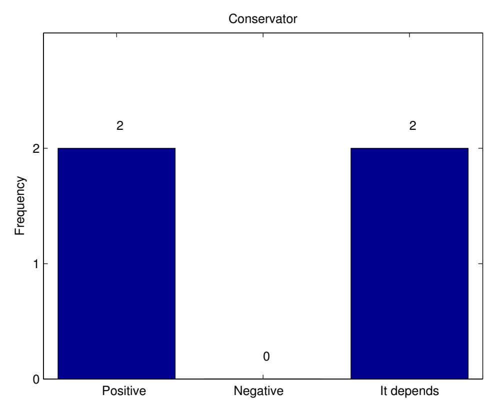


Figure 5.17: *The attitude toward a real-time painting viewer where you can change lighting and magnification interactively by all respondents.*

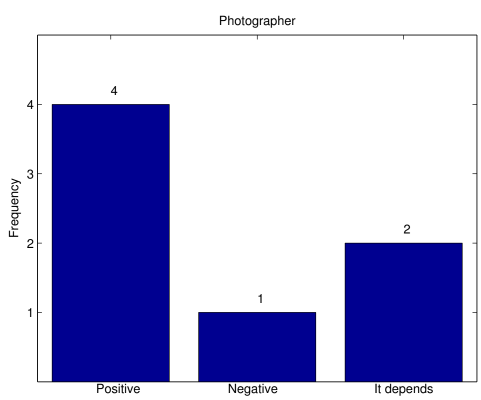
The attitude toward such as a system was also analyzed based on respondents' background in Fig. 5.18. While artists were not so sure about the system for various reasons, (e.g., affordability;) photographers and others were generally favorable to the system. The curator thought it might help:" Maybe it could help."



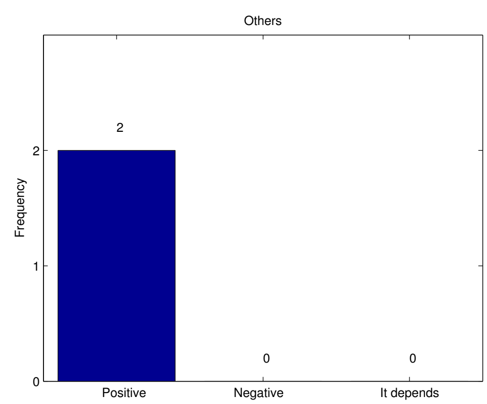
(a) *Artist*



(b) *Conservator*



(c) *Photographer*



(d) *Others*

Figure 5.18: *The attitude toward a real-time painting viewer where you can change lighting and magnification interactively by respondents in different groups.*

Q9. The Munsell Color Science Laboratory has a commitment to performing research in support of art conservation science, artwork imaging, archiving, and reproduction, and to characterizing the material appearance of artwork. List research topics we should consider in the near future.

The answers varied widely depending on respondents' background, and they are listed in Tables 5.5 to 5.9.

Table 5.5: *The suggested research topics by artists.*

Topic	Number
Art education	1
Color perception (synesthesia)	1
Color mixing (pigment, colorant)	3

Table 5.6: *The suggested research topics by photographers.*

Topic	Number
Digital imaging and color management	3
Guidelines of fine art reproduction	2
RTI	1
Artwork appearance	1

Table 5.7: *The suggested research topics by conservators.*

Topic	Number
LED lighting in museums	1
How artworks is viewed and evaluated (viewing condition)	1

Table 5.8: *The suggested research topics by the curator.*

Topic	Number
Modeling for 3D digital reproductions measure methods for color rendering of various light sources	1

Table 5.9: *The suggested research topics by others.*

Topic	Number
Digital restoration of faded artwork	1
Digital print inks	1

5.1.2 Discussion

Based on the responses of the survey, artists and photographers were the majority of all the respondents, conservators as the third part, and only one curator took part in this survey. All of the respondents, except one curator, mentioned color and texture as the two most important properties, shown in Table 5.10. In terms of their background, their feedback about other physical properties are varied and included size, composition, squareness, minimum specular highlight, sharpness, and contrast. For photographers, considering the squareness and size when capturing the artwork is reasonable; artists preferred considering the composition of artwork. The selection of extreme lighting also depends on the background of the respondents. No one preferred using the directional light alone, half of the respondents wanted somewhere in between, and the other half thought the lighting is dependent on the painting. Based on the answers of lighting geometry, diffuse lighting was preferred overall. Some of the respondents pointed out that 45-degree lighting was used often. Nine respondents preferred daylight ($\geq 5000\ K$), D50 and D65, while a similar number of respondents preferred lighting with a lower CCT in the range of $3000\ K - 3500\ K$. Three respondents thought the color of the lighting was dependent on the types of galleries, paintings, and applications. Depending on the respondents' background, most conservators insisted on evaluating the reproductions with the presence of the original. Alternatively, artists were generally less critical of the availability of the original when assessing the image quality of the reproductions. Most respondents were not critical about the extra time needed to collect significantly more information ranging from a few days to as long as it takes. By comparison of their background, artists and photographers are more willing to spend extended periods of time relative to conservators. The attitude toward a real-time painting viewer system varied based on respondents' background; most respondents agreed that it was an interesting and useful application, and eight respondents believed that it depended on the painting. Artists were not so sure about the system due to several reasons such as affordability. The suggestions for future research topics also are collected and categorized by different groups and listed in Tables 5.5 to 5.9.

Table 5.10: *The comparison of properties that are of great importance when photographing the artwork by all respondents. The row number is the property index and the column is the background of respondents.*

Position	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Artists	color	texture	size	composition	squareness	min specular highlight	color
Conservators	color	texture	glossiness				
Photographers	color	texture	details	reflectance	squareness	min specular highlight	size
Curator	surface texture	glossiness					
Others	color	surface texture	min specular highlight				

This survey played a critical part in our effort to understanding the physical properties of paintings. From the responses, it is easy to see that a real-time painting viewer system with capability to change lighting and magnification interactively is advantageous. Based on the responses of the survey, several physical properties should be considered to evaluate the performance of different painting viewer systems, such as color and texture. On the other hand, reality is another important factor; this is suggested by the responses in favor of composition, squareness, details, and reflectance. Besides, 45-degree diffuse lighting is an important lighting geometry for an evaluation system. This survey provided several important criteria for the comparison of different painting viewer systems.

5.1.3 Conclusions

The survey was successful in gaining insight to critical criteria when imaging paintings. Based on the respondents of the survey, four questions were generated considering the most important surface physical properties when photographing an art painting. Four questions are listed below in Table 5.11 and used as judgment criteria in the second experiment of this research.

Table 5.11: *The questions generated from the survey.*

Number	Question
1	Which image looks most like the real painting?
2	Which image best conveys the painting's gloss/shininess?
3	Which image best conveys the painting's texture?
4	Which image best conveys the painting's color?

5.2 Experiment II - Psychophysical Evaluation

The next sections describe the psychophysical experiment comparing different quality criteria and different imaging systems.

5.2.1 Question A: Which Image Looks Most Like the Real Painting?

Question A was aimed at evaluating the total appearance of rendering paintings based on the different systems. Three paintings were tested in this question to investigate the performance of the different techniques in reproducing the paintings. Those paintings are "Tree," "Wheat Field," and "Tulip." The artist of "Tree" was Dr. Roy S. Berns, the author of "Tulip" was MCSL Phd student Brittany Hensley, and "Wheat Field" was purchased at a gift shop from an unknown artist.

5.2.1.1 "Tree"

The first tested painting was "Tree" which is a texture and color rich painting with spatially varying gloss. The colors were vibrant and highly contrasted. The texture was ubiquitous and diverse throughout the painting. The seven systems listed in Table 5.12 were tested, and the image quality of the reproductions based on these systems were evaluated in the paired comparison experiment. A great variation of color rendering can be seen in Fig. 5.19. For example, the image generated by the RTI system was usually darker than all the rest of the reproductions, and the image of the conventional soft-box system looked softer than the others. To avoid the distraction from the color shift of the RTI system compared to the other systems, the RTI system was adjusted to match the conventional stimulus, named RTIPs. But in this part, the purpose was to evaluate the total appearance of different systems, and color was a very important factor; therefore, the RTIPs system was omitted to keep the real appearance of the RTI system.

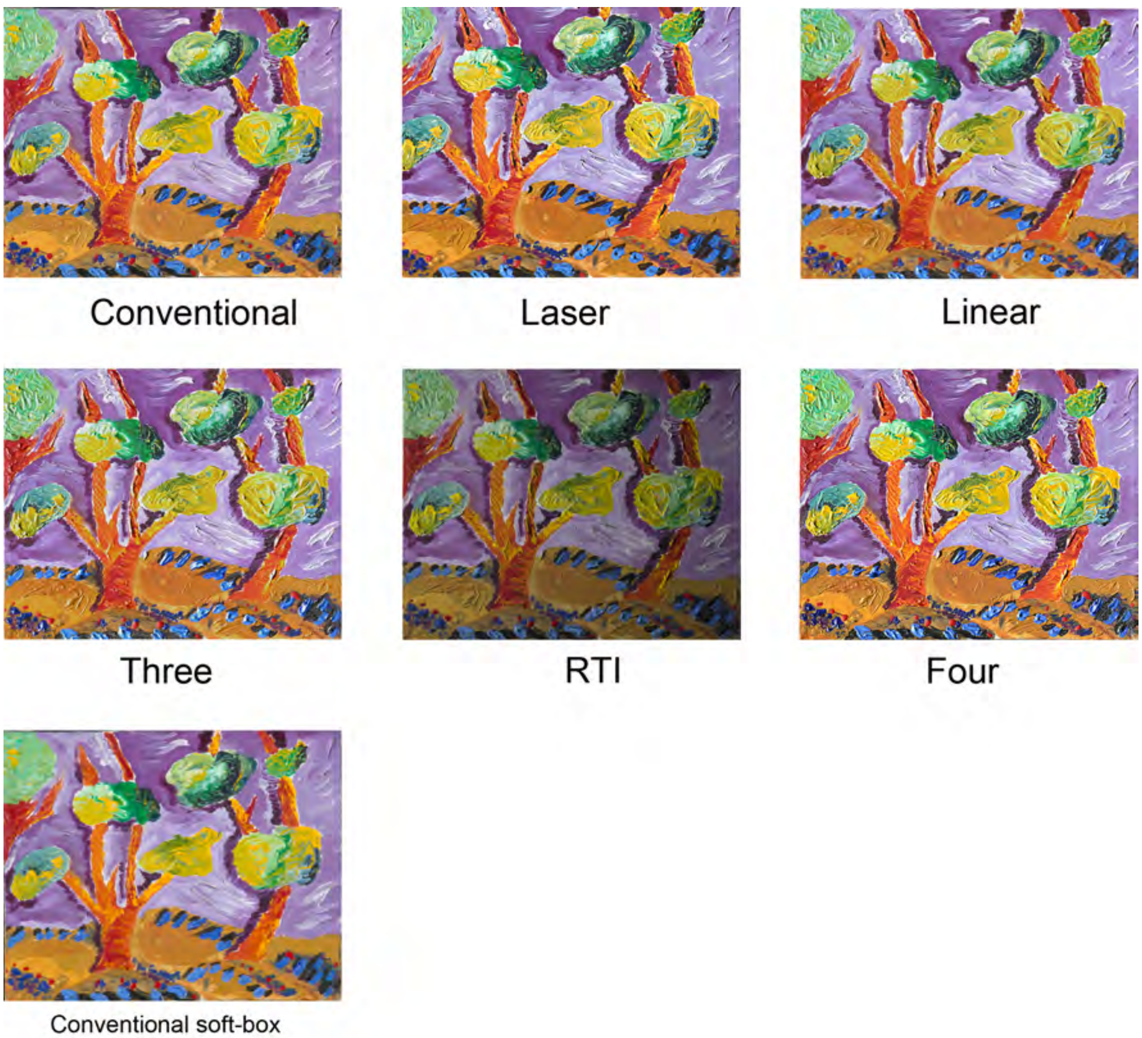


Figure 5.19: *Stimuli of Question A ("Tree").*

Table 5.12: *Stimuli of question A: "Tree."*

No.	Type	System	Tree
1	Image	Conventional	✔
2		Conventional soft-box	✔
3		Linear light	✔
4		Four-light	✔
5		Three-light	✔
6		RTI	✔
7		Laser scan	✔

In Table 5.13, the frequency of one reproduction preferred to another is shown in each cell. The 50% in the diagonal cells means that when the same reproduction is shown for paired comparison, either stimuli should be selected 50% of the time, as no difference exists between the pair of the same stimuli, an assumption made in this experiment in order to reduce the total number of comparisons. We assumed our data reflect the observer's choices, in general. For example, 48% (2nd column and 1st row) means that 48% of the time, one stimuli (linear) was preferred to the other (conventional).

By assuming that the frequency in Table 5.13 is normal distributed, Table 5.14 exists to help find the area of a z – value (or z – score). The interval scale values were calculated as the mean of the z-score values according to Eq. 2.21 for each system, and the final row shows the ranking order of the compared systems, described below.

Table 5.13: *Probability matrix of question A ("Tree"): Which image looks most like the real painting?*

		patch k						
		Conventional	Linear	Three	Four	RTI	Soft-box	Laser
patch j	Conventional	50%	48%	20%	64%	36%	4%	48%
	Linear	52%	50%	24%	64%	40%	4%	72%
	Three	80%	76%	50%	80%	48%	16%	76%
	Four	36%	36%	20%	50%	20%	1%	36%
	RTI	64%	60%	52%	80%	50%	24%	68%
	Soft-box	96%	96%	84%	99%	76%	50%	96%
	Laser	52%	28%	24%	64%	32%	4%	50%

Table 5.14: *Z scores matrix of question A ("Tree"): Which image looks most like the real painting?*

		patch k						
		Conv	Linear	Three	Four	RTI	Soft-box	Laser
patch j	Conventional	0.00	-0.05	-0.84	0.36	-0.36	-1.75	-0.05
	Linear	0.05	0.00	-0.71	0.36	-0.25	-1.75	0.58
	Three	0.84	0.71	0.00	0.84	-0.05	-0.99	0.71
	Four	-0.36	-0.36	-0.84	0.00	-0.84	-2.33	-0.36
	RTI	0.36	0.25	0.05	0.84	0.00	-0.71	0.47
	Soft-box	1.75	1.75	0.99	2.33	0.71	0.00	1.75
	Laser	0.05	-0.58	-0.71	0.36	-0.47	-1.75	0.00
	Interval scale	**0.38**	**0.25**	**-0.29**	**0.73**	**-0.18**	**-1.33**	**0.44**
	Rank	2	2	5	1	5	7	2

The performance of each method is visualized in Fig. 5.20. The abscissa axis is the system used to generate the reproductions, and the ordinate axis is the mean value of the z-score. Systems were ranked based on the values of interval scale and the confidence interval values. If the interval scale value was located within the 95% confidence interval values of other systems, then they were at the same level; otherwise, they were ordered by the interval scale value. The greater value of the z-score, the better the performance. In Fig. 5.20, "*" indicates the mean value of z-score (interval scale value), and the length of bar indicates the confidence interval. For example, the interval scale value of the four-light system was located beyond the other systems; while the mean values of z-score of laser, conventional, and linear systems were closer to each other and within their confidence interval range, and the interval value of the conventional soft-box system was much lower than the others. This indicates that the four-light system performed the best; the laser, conventional, and linear systems were equivalent; and the conventional soft-box system performed the worst.

The four-light system was ranked the best by the observers. Surprisingly, the system even superseded the conventional image captured by the camera. This was unexpected because this painting has appreciable spatially-varying gloss, not captured with the four-light system. The reason was that the four-light system enhanced the surface appearance compared with the conventional camera. Also the results of the laser system and linear system were located within 95% confidence interval relative to the conventional system. In other words, no statistical difference among the conventional, laser, and linear systems exists. The three-light and RTI system performed below the four-light, conventional, laser and linear systems. Between the three-light and RTI systems, observers almost made an even choice. The conventional soft-box system was the least preferred since it evened out most of the texture information. By comparison, the four-light system featured more texture details than for the conventional system as shown in Fig. 5.19. Our visual system possibly senses such texture thus making the four-light system preferred. For the "Tree" image, the relative ranking interval between the four-light system and the conventional system was relatively large, while the intervals between most of the other systems were fairly small. This result indicated that the four-light system did a good job in preserving the total appearance for texture-rich paintings such as the "Tree" image.

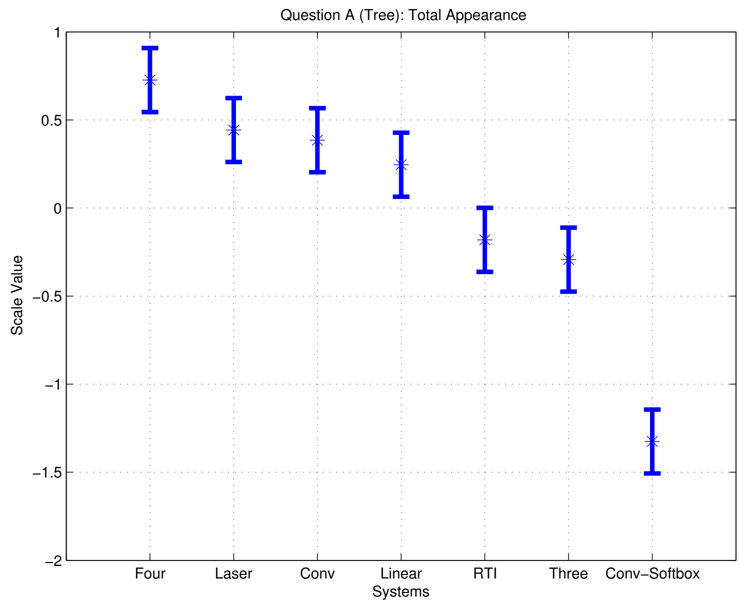


Figure 5.20: *Systems ranking of question A based on the painting "Tree." The x-axis is system name and y-axis is the interval-scale value (* locates the mean value of z-score and the length of bar indicates the confidence interval). The performance of system degrades from left to right. For example, four system performed the best among those seven systems, while the conventional soft-box system performed the worst.*

5.2.1.2 "Tulip"

The second tested painting, "Tulip," has more fine details than the other paintings and very sensitive colors of blue and purple throughout the whole painting. These characteristics are challenges for imaging systems. The image quality of the reproductions based on different systems were evaluated in the paired comparison experiment. Similar to the first painting, six systems, listed in Table 5.15, and the the real stimuli shown in Fig. 5.21 were tested. From Fig. 5.21, several stimuli have more fine blurry or fuzzy details than others such as the system. Also, a great variation of color rendering can be seen in Fig.

5.21. Similar to the previous painting, the image generated by the RTI system was darker than the other reproductions since the RTI system performed no color management. In addition, the image of the conventional soft-box system looked softer than the others.

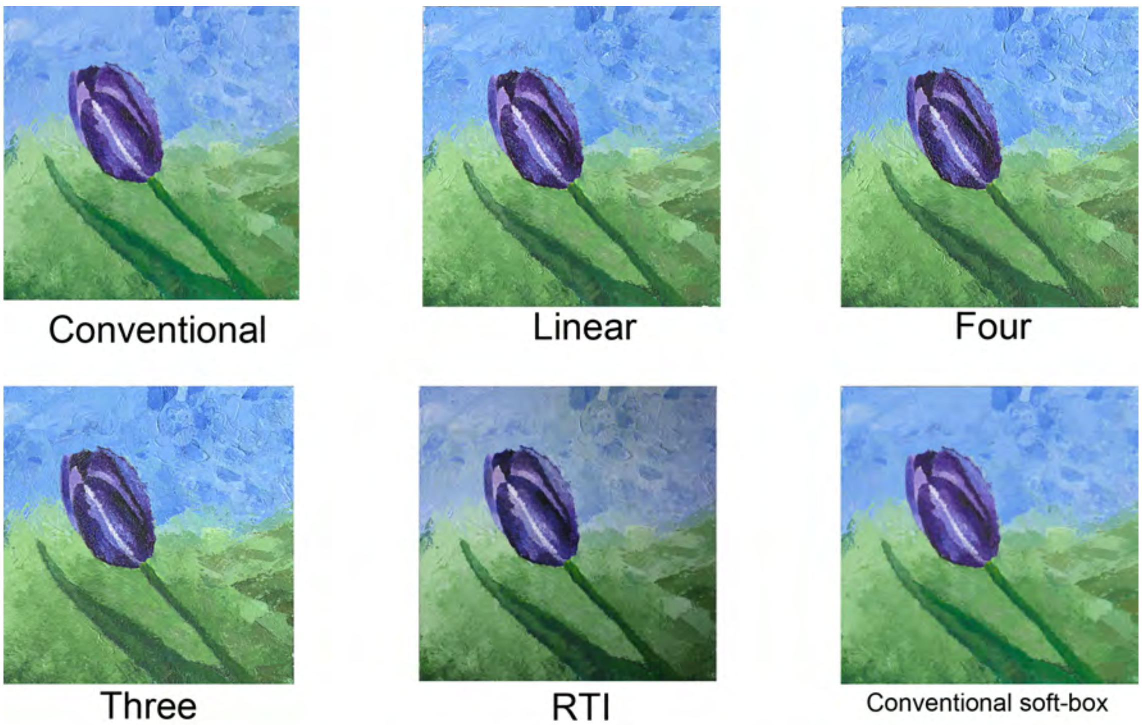


Figure 5.21: *Stimuli of Question A ("Tulip").*

Table 5.15: *Stimuli of question A: "Tulip".*

No.	Type	System	Tulip
1		Conventional	✔
2		Conventional soft-box	✔
3	Image	Linear light	✔
4		Four-light	✔
5		Three-light	✔
6		RTI	✔

The probability matrix of question A ("Tulip") is shown in Table 5.16, and the corresponding z-scores calculated based on Eq. 2.21- 2.23 are shown in Table 5.17.

Table 5.16: *Probability matrix of question A ("Tulip"): Which image looks most like the real painting?*

		patch k					
		Conventional	Linear	Three	Four	RTI	Soft-box
patch j	Conventional	50%	40%	4%	32%	16%	16%
	Linear	60%	50%	24%	60%	40%	32%
	Three	96%	76%	50%	92%	48%	60%
	Four	68%	40%	8%	50%	16%	28%
	RTI	84%	60%	52%	84%	50%	56%
	Soft-box	84%	68%	40%	72%	44%	50%

Table 5.17: *Z scores matrix of question A ("Tulip"): Which image looks most like the real painting?*

		patch k					
		Conventional	Linear	Three	Four	RTI	Soft-box
patch j	Conventional	0.00	-0.25	-1.75	-0.47	-0.99	-0.99
	Linear	0.25	0.00	-0.71	0.25	-0.25	-0.47
	Three	1.75	0.71	0.00	1.41	-0.05	0.25
	Four	0.47	-0.25	-1.41	0.00	-0.99	-0.58
	RTI	0.99	0.25	0.05	0.99	0.00	0.15
	Soft-box	0.99	0.47	-0.25	0.58	-0.15	0.00
	Interval scale values	**0.74**	**0.15**	**-0.68**	**0.46**	**-0.41**	**-0.27**
	Rank	1	3	6	2	4	4

The final ranking result is shown in Fig. 5.22. By observing Fig. 5.22, one can see the conventional system best reproduced the total appearance of the tulip painting. The following ranking order of other systems was four-light, linear, conventional soft-box, RTI and three-light system. In Fig. 5.22, significant differences exist among systems except the conventional soft-box and RTI systems as determined from the relative ranking values and confidence intervals. The value of RTI is located within the scale of the conventional soft-box system, therefore, these two systems do not have obvious differences. By analyzing the order, one can see that the four-light system performs a much better job than the three-light system. The reason might be that the four-light system generates more accurate surface normals than the three-light system and reduces more image noise. The observers preferred the conventional soft-box system which has a few texture details or the RTI system, which often looks darker rather than a very fuzzy or blurry three-light image. The linear system is ranked in the middle among those six techniques.

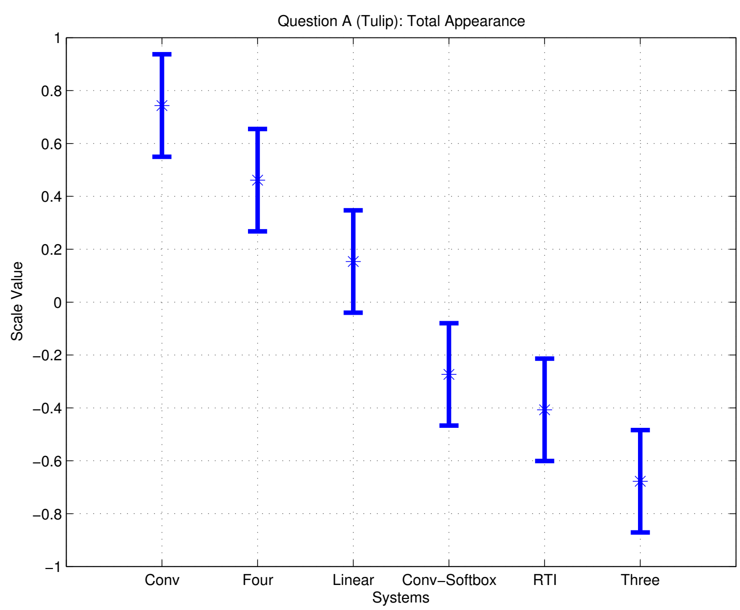


Figure 5.22: *Ranking order of Question A ("Tulip"). The performance of system degrades from left to right.*

5.2.1.3 "Wheat Field"

The third tested painting was "Wheat field" that has many brush details having been painted in the style of Vincent Van Gogh. The same systems as "Tulip" were evaluated in the paired comparison experiment, listed in Table 5.18. The stimuli are shown in Fig. 5.23 and a similar situation occurred; the RTI system was darker than all the rest of the reproductions and the image of the conventional soft-box system looked softer than the others. In terms of this situation, those systems performed very consistently.

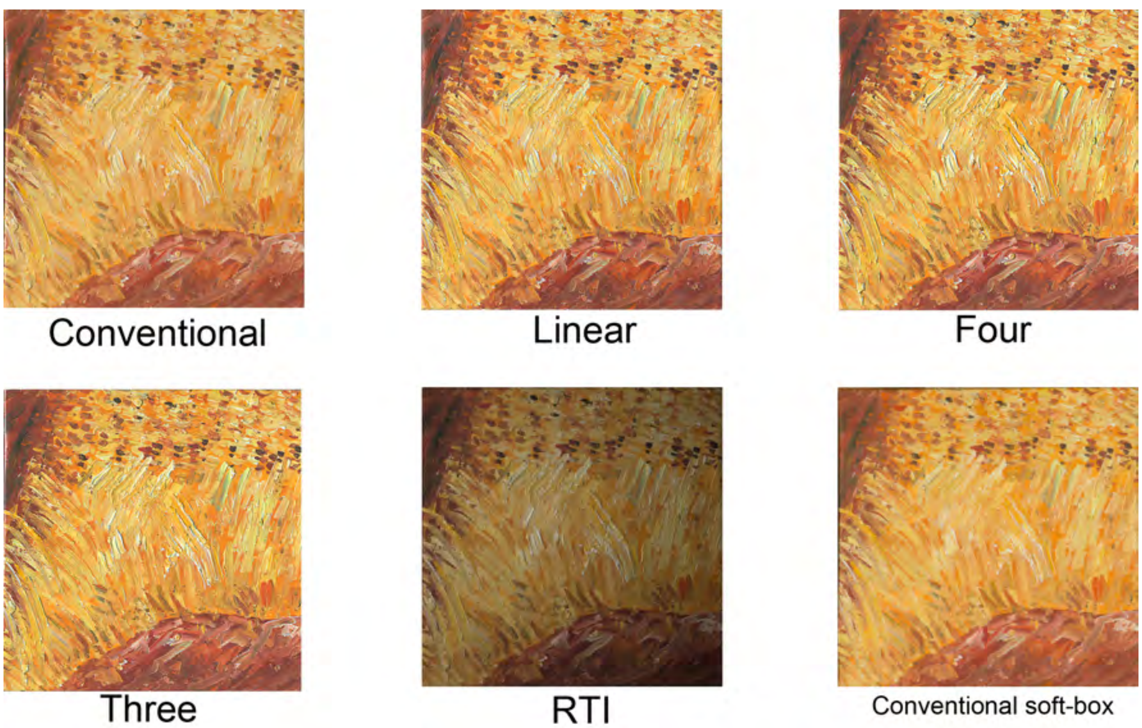


Figure 5.23: *Stimuli of Question A ("Wheat field").*

Table 5.18: *Stimuli of question A: "Wheat field."*

No.	Type	System	Wheat field
1	Image	Conventional	✔
2		Conventional soft-box	✔
3		Linear light	✔
4		Four-light	✔
5		Three-light	✔
6		RTI	✔

The probability matrix of question A ("Wheat field") is shown in Table 5.19, and the corresponding z-scores is shown in Table 5.20.

Table 5.19: *Probability matrix of question A ("Wheat field"): Which image looks most like the real painting?*

		patch k					
		Conventional	Linear	Three	Four	RTI	Soft-box
patch j	Conventional	50%	20%	40%	20%	20%	4%
	Linear	80%	50%	84%	60%	40%	12%
	Three	60%	16%	50%	56%	40%	8%
	Four	80%	40%	44%	50%	32%	8%
	RTI	80%	60%	60%	68%	50%	28%
	Soft-box	96%	88%	92%	92%	72%	50%

Table 5.20: *Z scores matrix of question A ("Wheat field"): Which image looks most like the real painting?*

		patch k					
		Conventional	Linear	Three	Four	RTI	Soft-box
patch j	Conventional	0.00	-0.84	-0.25	-0.84	-0.84	-1.75
	Linear	0.84	0.00	0.99	0.25	-0.25	-1.17
	Three	0.25	-0.99	0.00	0.15	-0.25	-1.41
	Four	0.84	-0.25	-0.15	0.00	-0.47	-1.41
	RTI	0.84	0.25	0.25	0.47	0.00	-0.58
	Soft-box	1.75	1.17	1.41	1.41	0.58	0.00
	Interval scale values	**0.75**	**-0.11**	**0.37**	**0.24**	**-0.21**	**-1.05**
	Rank	1	4	2	2	4	6

The final result for "Wheat Field" is shown in Fig. 5.24. From Fig. 5.24, the conventional system performed the best among those systems and has obvious differences compared with the others. The three-light and four-light system performed equally. Following those are the linear and RTI systems; the conventional soft-box system performed the poorest since it failed to present the glossy texture contents in the image.

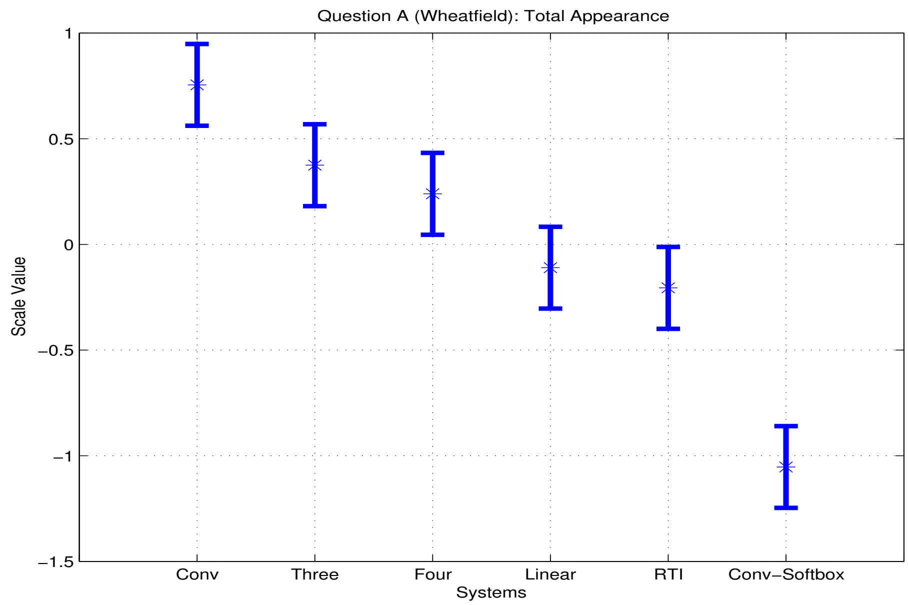


Figure 5.24: *Ranking order of Question A ("Wheat field").*

5.2.1.4 Combined Results

Based on the results of the three paintings, the total performance of the different systems listed in Table 5.21 was evaluated.

Table 5.21: *Stimuli of question A.*

No.	Type	System	Tree	Tulip	Wheat field
1	Image	Conventional	✔	✔	✔
2		Conventional soft-box	✔	✔	✔
3		Linear light	✔	✔	✔
4		Four-light	✔	✔	✔
5		Three-light	✔	✔	✔
6		RTI	✔	✔	✔

The total probability matrix of question A is shown in Table 5.22 and the corresponding z-scores are shown in Table 5.23.

Table 5.22: *Probability matrix of question A (Total): Which image looks most like the real painting?*

		patch k					
		Conventional	Linear	Three	Four	RTI	Soft-box
patch j	Conventional	50%	36%	21%	39%	24%	8%
	Linear	64%	50%	44%	61%	40%	16%
	Three	79%	56%	50%	76%	45%	28%
	Four	61%	39%	24%	50%	23%	12%
	RTI	76%	60%	55%	77%	50%	36%
	Soft-box	92%	84%	72%	88%	64%	50%

Table 5.23: *Z scores matrix of question A (Total): Which image looks most like the real painting?*

		patch k					
		Conventional	Linear	Three	Four	RTI	Soft-box
patch j	Conventional	0.00	-0.36	-0.79	-0.29	-0.71	-1.41
	Linear	0.36	0.00	-0.15	0.29	-0.25	-0.99
	Three	0.79	0.15	0.00	0.71	-0.12	-0.58
	Four	0.29	-0.29	-0.71	0.00	-0.75	-1.16
	RTI	0.71	0.25	0.12	0.75	0.00	-0.36
	Soft-box	1.41	0.99	0.58	1.16	0.36	0.00
	Interval scale values	**0.51**	**0.02**	**-0.24**	**0.42**	**-0.28**	**-0.89**
	Rank	1	3	4	1	4	6

The final result is shown in Fig. 5.25. The performance can be divided into four levels. In order of best to worst performance, the first level consisted of the conventional system and the four-light system; the second level was the linear system; the third consisted of the three-light system and RTI system; and fourth level, the conventional soft-box system, performed the worst. In terms of this ranking order, one can safely conclude that the conventional system can be replaced by the four-light system. The four-light system generated from images taken at $45^o/0^o$ could produce a rendering at 60^o that was equivalent to taking an image at 60^o. Comparison of different levels shows that each level had significant differences. However, the performance for individual paintings may vary. For example, the three-light system performed better for “Wheat field” compared to the other two paintings. In general, the ranking order was very similar. Considering evaluation of the total appearance of the real paintings, the result can be summarized that the conventional system and four-light system performed better than the linear, the three-light system, the RTI, and the conventional soft-box system. The linear system was ranked just after the conventional system and the four-light system revealing that inexperienced observers were not put off by a lack of spatially varying gloss. The conventional soft-box system (diffuse lighting) was always the least preferred for total appearance since many of the texture details were blurred by the lighting.

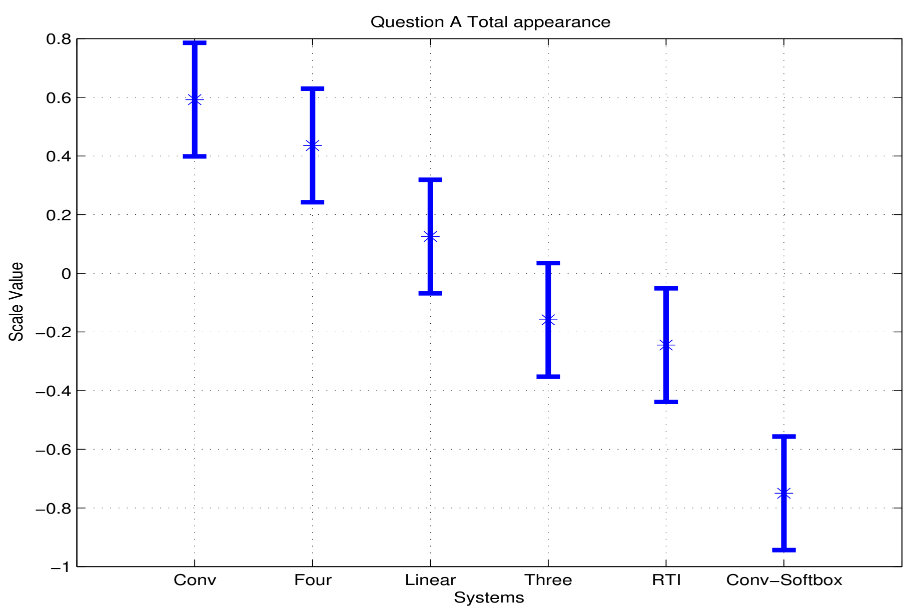


Figure 5.25: *Analysis of Question A (Total).*

5.2.2 Question B: Which Image Best Conveys the Painting's Gloss/Shininess?

For this section, the painting "Tree" was used to evaluate the performance of the six different techniques, listed in Table 5.24. The reason for choosing the "Tree" was that this painting had spatially varying gloss, while the other paintings had uniform gloss. Comparing the stimuli shown in Fig. 5.26, a large range of observable gloss exists among the six systems. For example, gloss was barely noticed in the conventional soft-box system at all. The three-light system was omitted because the three-light system shared similar characteristics as the four-light system and generally performed inferior to the four-light system.

Table 5.24: *Stimuli of question B.*

No.	Type	System	Tree
1	Image	Conventional	✔
2		Conventional soft-box	✔
3		Four-light	✔
4		Linear light	✔
5		RTI	✔
6		Laser scan	✔

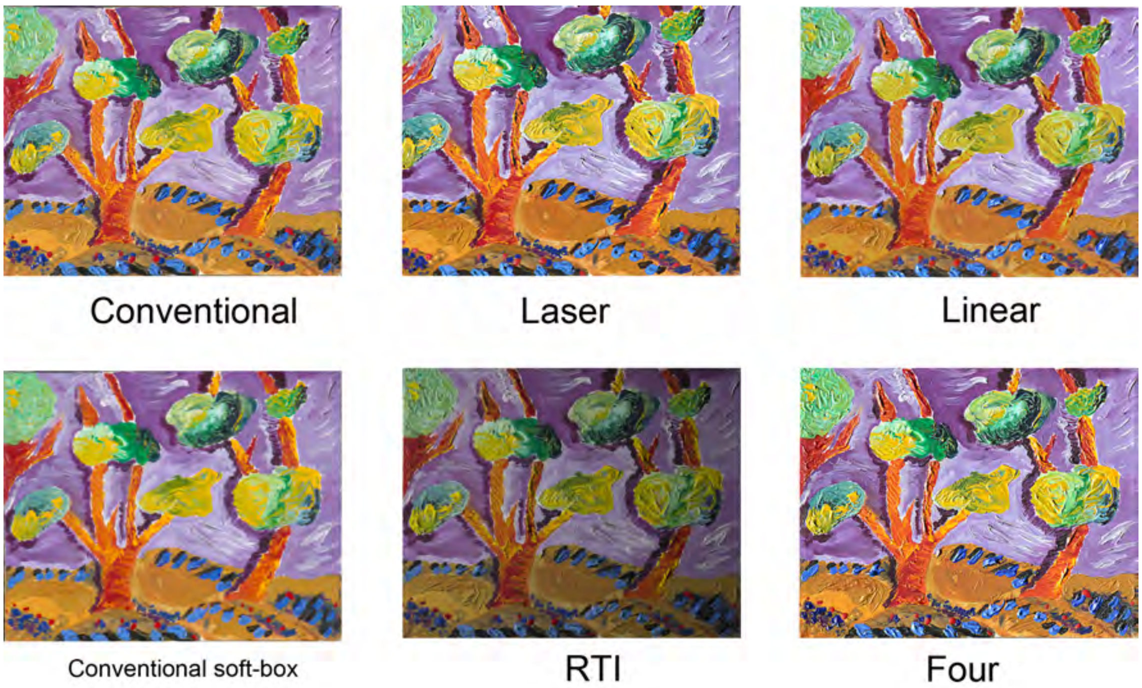


Figure 5.26: *Stimuli of Question B ("Tree").*

The probability matrix of question B is shown in Table 5.25 and the corresponding z-scores are shown in Table 5.26. Corresponding to the observation of stimuli, 4% (the third row, the seventh column) of the time, the conventional soft-box system was preferred over the conventional system.

Table 5.25: *Probability matrix of question B: Which image best conveys the painting's gloss/shininess?*

		patch k					
		Conventional	Linear	Four	RTI	Soft-box	Laser
patch j	Conventional	50%	44%	44%	16%	4%	36%
	Linear	56%	50%	28%	20%	4%	40%
	Four	56%	72%	50%	28%	24%	56%
	RTI	84%	80%	72%	50%	24%	84%
	Soft-box	96%	96%	76%	76%	50%	92%
	Laser	64%	60%	44%	16%	8%	50%

Based on Table 5.26 and Fig. 5.27, one can see that the linear system performed equally well to the conventional system, followed by the laser, the four-light, RTI, and conventional soft-box systems. These results make sense because the linear system and the conventional system can produce the real specular highlights, while the other systems cannot. The laser system and four-light system are almost located at the same level since they were generated from the same BRDF model for gloss. The laser system performed slightly better than the four-light system. This is most likely because the specular reflectance was affected by adjusting the roughness parameter in order to obtain more details when generating four-light system images. The RTI performed weakly in revealing gloss possibly because it was simply using a metallic BRDF model blended with the actual image. The conventional soft-box system image still performed the poorest since it looked blurred and without the appearance of gloss.

Table 5.26: *Z scores matrix of question B: Which image best conveys the painting's gloss/shininess?*

		patch k					
		Conventional	Linear	Four	RTI	Soft-box	Laser
patch j	Conventional	0.00	-0.15	-0.15	-0.99	-1.75	-0.36
	Linear	0.15	0.00	-0.58	-0.84	-1.75	-0.25
	Four	0.15	0.58	0.00	-0.58	-0.71	0.15
	RTI	0.99	0.84	0.58	0.00	-0.71	0.99
	Soft-box	1.75	1.75	0.71	0.71	0.00	1.41
	Laser	0.36	0.25	-0.15	-0.99	-1.41	0.00
	Interval scale values	**0.57**	**0.55**	**0.07**	**-0.45**	**-1.05**	**0.32**
	Rank	1	1	4	5	6	3

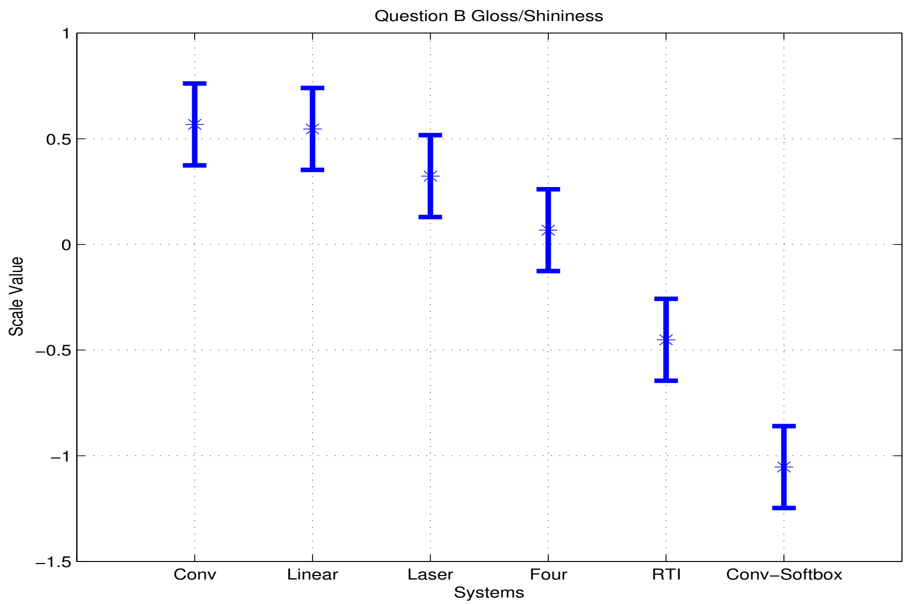


Figure 5.27: *Analysis of Question B.*

5.2.3 Question C: Which Image Best Conveys the Painting's Texture?

Texture is another very important characteristic based on results of the survey on digitization issues of physical properties of paintings. In this part of the experiment, the image stimuli and surface normal gray maps were included to compare with each other. The gray maps were included so that only texture information could be compared between the images. Because this question was aimed at evaluating texture property, the RTIPs system was used to avoid a distraction because of the RTI image's poor color. The RTI system looked different compared to the other systems. Also, the original RTI images were included. Furthermore, only the four-light, linear, and laser scan systems have information of the surface normals. The results of surface normal data were very noisy. The stimuli utilized are listed in Table 5.27 and Fig. 5.28.

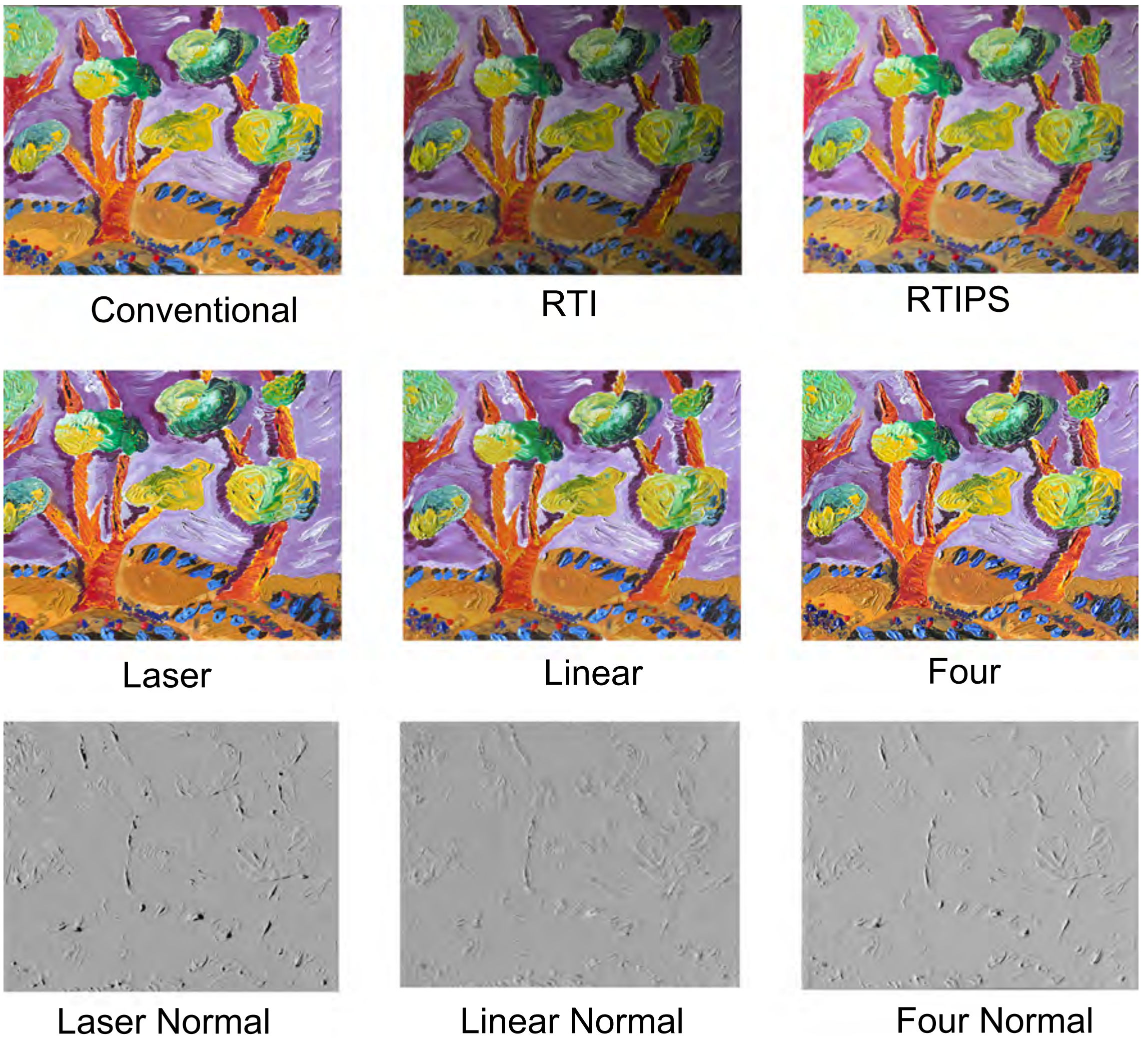


Figure 5.28: *Stimuli of Question C ("Tree").*

Table 5.27: *Stimuli of question C.*

No.	Type	System	Tree
1	Image	Conventional	✔
2		Four-light	✔
3		Linear	✔
4		RTI	✔
5		RTIPs	✔
6		Laser scan	✔
7	Surface normal	Four-light (surface normal)	✔
8		Linear (surface normal)	✔
9		Laser scan (surface normal)	✔

The total probability matrix of Question C is shown in Table 5.28 and the corresponding z-scores are shown in Table 5.29. From Table 5.28, high probability values were concentrated at the four-light surface normal, the laser scan surface normal, and the conventional system. The percentage values of RTIPs system was low relative to the other systems.

Table 5.28: *Probability matrix of question C: Which image best conveys the painting's texture?*

		patch k								
		Conv	Linear	Four	RTI	RTIPs	Laser	FourN	LinearN	LaserN
patch j	Conv	50%	36%	52%	36%	16%	56%	52%	28%	68%
	Linear	64%	50%	60%	56%	24%	64%	76%	68%	76%
	Four	48%	40%	50%	36%	44%	56%	44%	52%	40%
	RTI	64%	44%	64%	50%	36%	64%	76%	28%	52%
	RTIPs	84%	76%	56%	64%	50%	72%	76%	44%	56%
	Laser	44%	36%	44%	36%	28%	50%	56%	44%	36%
	FourN	48%	24%	56%	24%	24%	44%	50%	12%	48%
	LinearN	72%	32%	48%	72%	56%	56%	88%	50%	80%
	LaserN	32%	24%	60%	48%	44%	64%	52%	20%	50%

Table 5.29: *Z scores matrix of question C: Which image best conveys the painting's texture?*

		patch k								
		Conv	Linear	Four	RTI	RTIPs	Laser	FourN	LinearN	LaserN
patch j	Conv	0.00	-0.36	0.05	-0.36	-0.99	0.15	0.05	-0.58	0.47
	Linear	0.36	0.00	0.25	0.15	-0.71	0.36	0.71	0.47	0.71
	Four	-0.05	-0.25	0.00	-0.36	-0.15	0.15	-0.15	0.05	-0.25
	RTI	0.36	-0.15	0.36	0.00	-0.36	0.36	0.71	-0.58	0.05
	RTIPs	0.99	0.71	0.15	0.36	0.00	0.58	0.71	-0.15	0.15
	Laser	-0.15	-0.36	-0.15	-0.36	-0.58	0.00	0.15	-0.15	-0.36
	FourN	-0.05	-0.71	0.15	-0.71	-0.71	-0.15	0.00	-1.17	-0.05
	LinearN	0.58	-0.47	-0.05	0.58	0.15	0.15	1.17	0.00	0.84
	LaserN	-0.47	-0.71	0.25	-0.05	-0.15	0.36	0.05	-0.84	0.00
	Interval scale values	**0.18**	**-0.26**	**0.11**	**-0.08**	**-0.39**	**0.22**	**0.38**	**-0.33**	**0.17**
	Rank	2	7	2	6	7	2	1	7	2

By observing Table 5.29 and Fig. 5.29, the four-light surface normal system significantly outperforms other systems, which means this system generated the best property of texture. The laser, conventional, laser surface normal, and four-light image system received the same level of the ranking based on the relative ranking values. The RTI system ranked as the next lower level and then linear, linear surface normal, and RTIPs systems. Interestingly, the linear system performance was not as good as expected and a possible reason was that the appearance was affected by the high amount of noise in the image. Also, the RTIPs system performed the poorest because the color looked very different from the other stimuli, which affected the result to some degree. Although the purpose of the RTIPs system was to reduce the color offset by RTI, the corrected color also suppressed the surface texture and did not help improve the visual ranking.

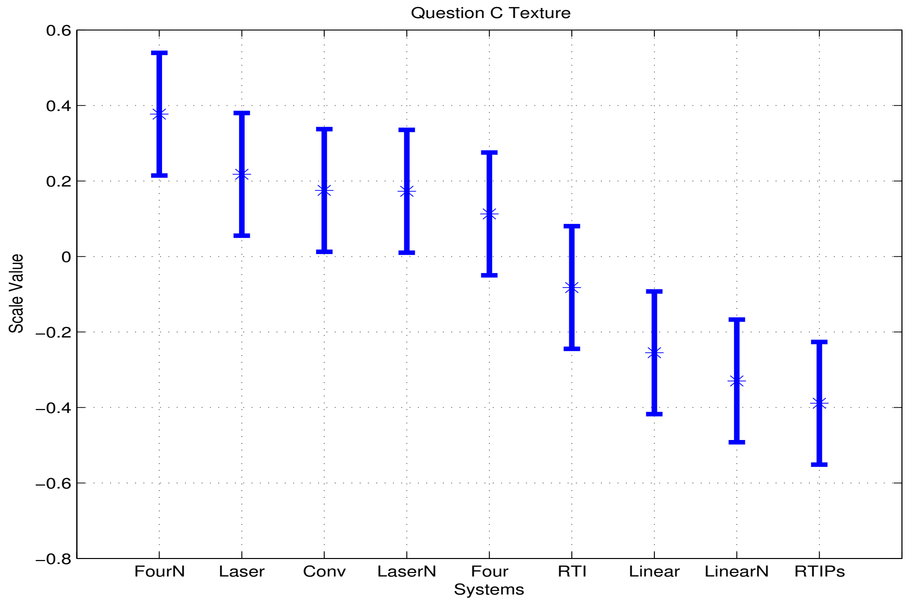


Figure 5.29: *Analysis of Question C.*

5.2.4 Question D: Which Image Best Conveys the Painting's Color?

Color is another important factor in evaluating a painting's appearance (Berns, 2000). Color was evaluated for the five systems that are listed in Table 5.30, while stimuli are shown in Fig. 5.30. The color information of the linear system came from the four-light system. The linear system could not generate diffuse albedo. The three-light system was omitted since it used the same method to reproduce color information as the four-light system. The RTI system was not included because it did not perform well in color management, and the color appearance looked significantly different from the other five systems.

Table 5.30: *Stimuli of question D.*

No.	Type	System	Tree
1	Image	Conventional	✔
2		Conventional soft-box	✔
3		Linear light	✔
4		Four-light	✔
5		Four-light diffuse albedo	✔

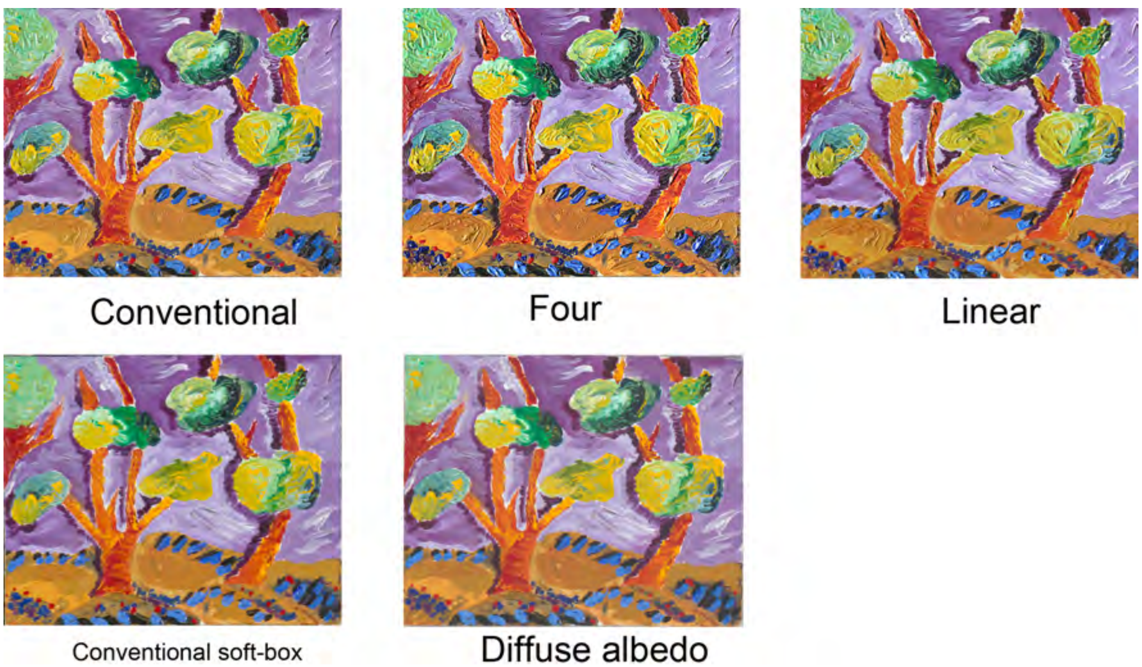


Figure 5.30: *Stimuli of Question D ("Tree").*

The total probability matrix of question D is shown in Table 5.31, and the corresponding z-scores are shown in Table 5.32. From Table 5.31, the values of percentage do not vary much. This may be because they have similar color appearance and the observers had difficulty distinguishing between them.

Table 5.31: *Probability matrix of question D: Which image best conveys the painting's color?*

		patch k				
		Conventional	Linear	Four	Soft-box	Diffuse
patch j	Conventional	50%	52%	44%	28%	24%
	Linear	48%	50%	52%	36%	32%
	Four	56%	48%	50%	32%	24%
	Soft-box	72%	64%	68%	50%	40%
	Diffuse albedo	76%	68%	76%	60%	50%

Table 5.32: *Z scores matrix of question D: Which image best conveys the painting's color?*

		patch k				
		Conventional	Linear	Four	Soft-box	Diffuse
patch j	Conventional	0.00	0.05	-0.15	-0.58	-0.71
	Linear	-0.05	0.00	0.05	-0.36	-0.47
	Four	0.15	-0.05	0.00	-0.47	-0.71
	Soft-box	0.58	0.36	0.47	0.00	-0.25
	Diffuse albedo	0.71	0.47	0.71	0.25	0.00
	Interval scale values	**0.28**	**0.17**	**0.21**	**-0.23**	**-0.43**
	Rank	1	1	1	4	4

The conventional, four-light, and linear systems performed the best as shown in Table 5.32 and Fig. 5.31. The method of the linear system and four-light system used to recover diffuse color performed well, and the color could be equivalent to the conventional system. The conventional soft-box and diffuse systems performed worse than the other three systems. The reason might be the results were affected by some other characteristics, such as texture or gloss since the choice might still be determined from the total appearance even though the question was targeted for only color appearance.

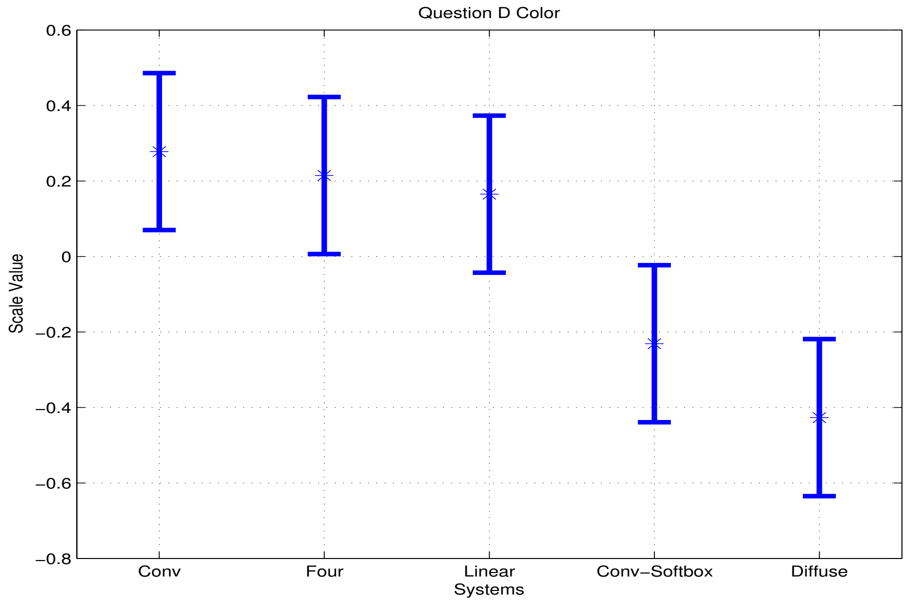


Figure 5.31: *Analysis of Question D.*

Chapter 6

Conclusions and Future Research

6.1 Conclusions

The goal of this thesis was to evaluate the performance of different systems capable of representing the total appearance of paintings. The total appearance of paintings includes not only spatially varying spectral reflectance but also gloss and texture. Eight systems were used to render the total appearance of art paintings.

A survey was conducted at first to understand the physical properties of a painting that are of great importance when reproducing a piece of artwork, how artwork reproductions can be best evaluated, and the usefulness of a real-time painting viewer. The survey was answered by 23 experts in fields related to art paintings, including photographers, conservators, artists, and a curator. This survey played a critical role in our effort to understanding the physical properties of paintings. Based on the responses of the survey, several physical properties should be considered to evaluate the performance of different painting viewer systems, such as color and texture. Additionally, from the responses, one can conclude that a real-time painting viewer system with the capability to change lighting and magnification interactively is advantageous. This survey provided several important criteria for the comparison of different painting viewer systems. Four questions were generated in response to the survey, and they were used to evaluate the performance of the different systems.

The performances of the eight systems were evaluated using psychophysical paired comparison experiments and executed by naive observers (composed of color science and imaging science students). The conclusions are summarized below.

For total appearance, the conventional system, the four-light system, and the laser system (only based on "Tree") performed the best, followed by the linear system, the three-light, and the RTI systems; the conventional soft-box system performed the poorest. From the experimental results, one can conclude that the conventional system can be replaced by the four-light system or the laser system since no obvious discrimination was made among these three systems, as determined from their relative ranking values and 95% confidence interval scale. Although the performance for individual paintings may vary, the following general result can be concluded. The conventional, four-light, and laser systems perform better than the linear, three-light, RTI, and conventional soft-box systems.

For glossy paintings, the linear system performed as well as the conventional system, then the laser, the four-light, and the RTI system; the last was the conventional soft-box system. This result makes sense because the linear and laser systems produced actual specular data, while the others could not reproduce the specular appearance with sufficient accuracy.

For texture-rich artwork, the rendered surface normal using four-light system significantly outperformed the other systems, which means this system best reproduces the property of texture. By comparison, the laser, conventional, laser surface normal, and four-light image systems perform similarly. The RTI system was ranked as the next lowest level followed by the linear, linear surface normal, and RTIPs systems. The inaccurate color representation affected the result of the RTI systems.

For color, the conventional, four-light, and linear systems performed the best and they ranked at the same level. The conventional soft-box and the diffuse systems performed worse than the other three systems. This might occur because the results are affected by some other characteristics, such as texture or gloss.

6.2 Future Research

6.2.1 Psychophysical Experiments

- Question Generation

Another survey would be good to have since only twenty-three respondents (relative to total 200 population) answered that survey. More appropriate questions could be prepared for the psychophysical experiment. Extra questions could be asked to judge how far the images are from the original painting in absolute terms, e.g. are they are relatively good reproductions, terrible reproductions, or some mix?

- Observers

Twenty-five observers took part in the experiment; more observers may generate more accurate results in the future. Also, the psychophysical experiment might be conducted by professional observers such as museum conservators who have more knowledge about the total appearance of paintings. The experiment was executed by inexperienced observers (color science and imaging science college students), and their preference of total appearance may vary from museum professions and artists.

- Stimuli

In this research, only one geometry was chosen. The lights illuminating the painting were 60° from the painting's normal and positioned at its left side. Different geometries of illumination and viewing angle may affect the rankings for these systems.

6.2.2 Technical Improvements

More techniques should be explored to make our comparison more complete. In turn, these systems can collect an even larger set of physical properties including color diffuse albedo, specular albedo, surface normal, gloss, and even real height maps of the painting. Although, the eight systems could successfully reconstruct the total appearance of the art paintings, there still are some problems affecting the final rendering, such as depth, and shadowing. For example, surface normals of an object describe the orientations of each point on the surface, often with an ambiguity of π in the surface tilt. This means that not enough information exists to compute surface shape. Usually people recover the surface shape via some integration process based on assumptions of smooth or constant surfaces. Construction through the integration of surface gradients is sensitive to noise and the integration paths across the surface. Also, generating shadows is difficult when rendering the images under certain illuminations. Therefore, the reality of the rendering was affected to some degree. Improving the quality of the measured surface properties is still a challenging topic; however, with advances new computer graphics rendering techniques, more accurate and robust reproductions of art paintings.

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